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Solar water heating systems and their market trends

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One of the most widely known solar thermal applications is solar water heating. In terms of installation expenditures and energy cost over the total life of the system, solar water heating technology has proven to be cost efficient for several domestic and industrial applications. Technological practicability of these systems has long been recognized and is presently employed in commercial sectors of many countries. This paper presents an overview of various types of solar assisted water heating systems and their market potential. Residential solar water heating is a promising age old technology, which has been evolved and developed both in the range and quality as a successful packaged market–product. The first part of this paper analyzes the performances along with how unique they are of different types of solar water heating systems and the later part of the paper covers its economic aspects.

Contents

1. Introduction

Renewable energy sources have the capacity to play a significant role in replacing conventional fuels in four distinct zones, such as electric power production, hot water production, transportation of fuels, and countryside (off-grid) power services. Fig. 1 represents the average annual growth in various renewable energy sectors, and by 2010 over 100 countries had initiated policy targets or promotion incentives related to renewable energy. Since 1980 the use of solar technology has increased at a rate of about 30% yearly [1]. In 2010, Renewable Energy Policy Network has reported that about 70 million houses are now using solar water heating (SWH) systems worldwide [2]. The economic benefits of the utilization of SWH can mainly be realized through savings in fuel costs for water heating and environmental issues.

SWH systems are becoming widespread and are now contributing significantly to both domestic and industrial sectors in several countries. China currently dominates the global solar thermal market.

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Nomenclature

COP	coefficient of performance
CPC	compound parabolic collector
DSWH	domestic solar water heating
DWH	domestic water heating
DX-SAHP	direct expansion solar assisted heat pump
ETHP	evacuated tube heat pipe
ETC	evacuated tube collector
FDM	finite-difference method
FPC	flat-plate collector
FPT	flat-plate with tubes
GIS	geographical information system
GSHP	ground source heat pump
GWP	global warming potentiality
HP	heat pump
HPSAHP	heat pipe solar assisted heat pump
ICS	integrated collector storage
ISAHP	integral-type solar assisted heat pump
MP	melting point
PCM	phase changing material
PHP	pulsating heat pipe
PV	photovoltaic
SASHP	solar air source heat pump
SF	solar fraction
SWH	solar water heater
T	temperature

Greek letters

η	efficiency
ε	exergy

Subscripts

o	ambient condition

Chinese companies manufactured 28 million square meters of system in 2009 which was above 80% of global solar hot water/heating output [2]. Apart from China, Germany, Turkey, Brazil, and India lead the solar hot water market. The European Union (EU) utilizes most portion of the remaining total installed SWH capacity. Germany marked a record in 2008 with an estimated SWH capacity of about 1.1 GW, but the new installations were slightly lower in 2009 [3]. Similarly, the government of Brazil targeted a reduction of more than 1000 MW additional energy installations by the year 2015 through the initiation of SWH systems [4]. On an average, about 20,000 SWH systems are being installed each year in India. On the other hand, the US domestic market capacity is still relatively small compared to the rest of the world but it is increasing. SWH market is also expanding in the countries of Africa, such as Ethiopia, Kenya, South Africa, Tunisia, and Zimbabwe. Palestine has the highest installation capacity among the countries of Middle Eastern and North African region. The capacity accounted for 68% of all the households that installed SWHs routinely in new buildings in that region.

As discussed above, although SWH systems have a huge prospectus, only a fraction of the projected possible utilization has been realized [5]. Fig. 2 shows the overall percentage of the World's installed SWH system in different regions. In 2010, the total installed capacity of SWH systems and space heating systems increased by an estimated 16%, reaching only about 185 GW of thermal energy globally (Table 1). As projected, the energy requirement by the year 2030 at about 0.6% more land will be required for 10% net efficient solar conversion systems [2].

In general, SWH technology is considered to be a matured one that has attained commercialization. Yet, there exists several opportunities to further improve the system performance for an

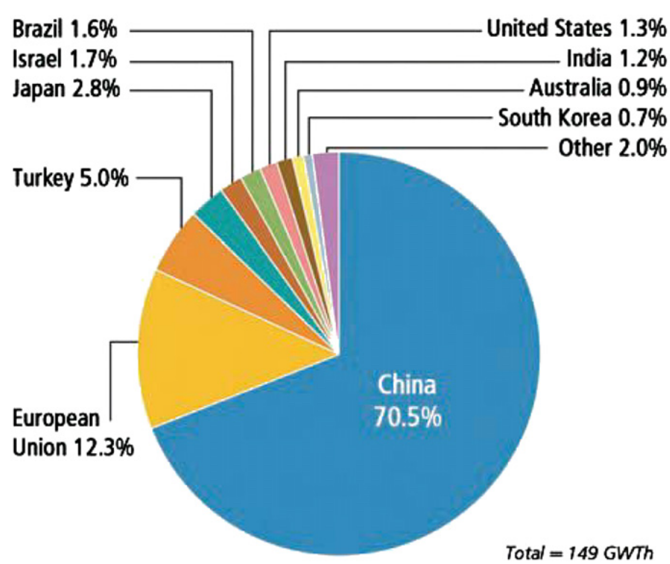

Fig. 2. Solar hot water heating: existing capacity, top 10 countries/regions published by REN21 global status report in 2010 [2].

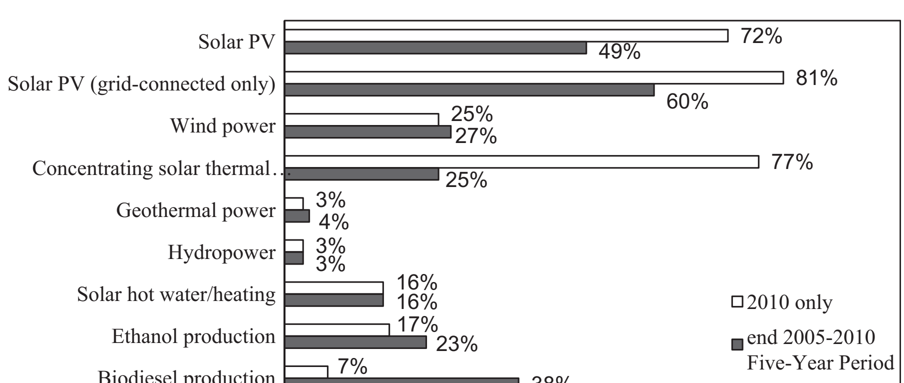

Fig. 1. Average annual growth rates of renewable energy capacity, 2005 to 2010 [132].

Table 1
Existing capacity of solar water heating from the year 2007 to 2010 [2,132].

Selected indicators	2007	2008	2009	2010
Renewable power capacity (existing, including hydro) (GW)	1085	1150	1230	1320
Solar hot water capacity (existing) (GW_{th})	125	130	160	185

increase in its reliability. Renewable energy research has become increasingly important since the signing of the Kyoto Protocol, and more work is being carried out in analyzing different aspects of SWH systems, such as collector design, storage tank, and different working fluids, to suit regional or specific geographical conditions. There exists distinct advantages and scope for SWH systems, and hence a detailed study on the performance of various types of SWH devices, including cost effectiveness and related economical factors of such systems are presented in this paper.

Table 2
Typical characteristic values for some transparent insulation material [79].

Insulation material	Thickness, (cm)	Transparency, τ (%)	Heat loss coefficient, U ($W/m^2/K$)
PMMA foam	1.6	58	3.6
Honeycomb structure	10	60	0.8
Aerogel pellets	1.6	53	1.25
Aerogel pellets evacuated	1.6	53	0.8

2. A brief history of solar water heating systems

SWH advanced from hypothesis to a prototype in the year 1767 by Swiss naturalist De Saussure, who built an insulated box painted black at its bottom with two panes of glass covering at the top [6]. He called it “Hot Box”, as the invention was capable of aiding in cooking, heating, and producing hot water. But the first commercial SWH, named Climax, was patented in the US by Clarence M. Kemp in 1891 [7]. His idea was further implemented as an integral collector storage solar water heater. Kemp placed a metal tank within a wooden box covered by a glass cover at the top part. His system produced hot water (38.8 °C) on sunny days. As an alternate to burning wood or expensive fuel for heating water, the SWH became popular in California and many other states very quickly. A third of all of the homes in Pasadena, California had SWH systems by 1897 [8]. In early 1900s, several researchers focused their attention in improving the design of the SWH system to make it durable and efficient. In 1909, William Bailey tailored the Kemp’s SWH system, by segregating it into two major parts; the solar thermal collector for collecting solar radiation along with storage tank for storing the produced hot water. Further, to prevent heat losses the storage tank was insulated. For the first time in the SWH field, William Bailey introduced the thermosyphon principle to aid the circulation of water in the collector and storage tank [9]. In 1950, Japan’s first commercial SWH was designed by Yamamoto by getting an inspiration from a view of a large bath tub, filled with water that was kept outside in the sunshine for a longer period of time. Later, SWH units based on the closed-pipe system were introduced.

Solar heated water was utilized for several applications. Until 1930, hot water for domestic purposes and for space heating were mainly engaged by the coal fired boilers [10]. SWH become a commercial product in the early 1960s. A typical SWH is of a thermosyphon kind that uses an absorber area of 3–4 m^2 flat-plate type solar collectors to energize a capacity of 150–180 l storage tank. One of the popular types of SWH systems is the forced circulation water heating system. Except for solar collectors, other accessory items such as the storage tank incorporated with piping, pump, and differential thermostat are usually kept indoors.

Solar assisted systems not only rely on the conventional mode of utilizing energy but also other systems, such as heat pump (HP) and photovoltaic thermal (PV/T). In 1927, HP technology was first patented by an English inventor T. G. N. Haldane [11]. However, before the 1960s, due to a record poor reliability of the HP units, the commercial distribution was very limited. Since then, research focus was directed on, and by the year 1970, the HP technology has been improved in quality and reliability. Moreover, the researchers had been motivated to find new alternative energy sources for energy production since the big oil crisis in 1973. This further aided the application of HP technology and it became widespread for both heating and cooling purposes. Although solar HP technology has shown higher efficiencies (400–600%) in respective functions, its capital cost is high, and hence it may not be suitable in places where cost of the system becomes a constraint [12,13].

Table 2). The production of SWH is now in packaged form and developed into a considerable business in the 21st Century. In countries such as China, Australia, Germany, Greece, Israel, and USA, the manufacturing of SWHs has become a part of the industrial sector. Self-motivation is a factor that worked behind the rapid expansion of SWH manufacturing industries in most parts of Europe. Currently, commercially available SWHs employ the following types as the packaged form: a system being operated by passive mode with an anti-freeze working fluid, solar-assisted heat pump system, a variety of evacuated solar collectors of both flat-plate and tubular in shape, and an active circulation system driven by pumps facilitating a wide range of flow rates.

3. Categorized studies conducted on SWH systems

Depending on the nature of heat transfer through the working fluid, SWH systems can be broadly classified into: direct systems and indirect systems. In the direct system, water is heated directly in the collector. In the indirect system, a heat transfer fluid is heated in the collector which is then passed through a condenser or a heat exchanging device to heat water. Similarly, depending on the circulation of working fluids, SWH systems can also be grouped into either: passive circulation system or active circulation system. Passive circulation systems refer to thermosyphonic method in which the density difference induces the circulation of the fluid, naturally. On the other hand, active circulation employs a pump to effect forced circulation of the working fluid. To overcome the freezing of the working fluid, during adverse weather conditions, different techniques have been employed such as recirculation or drain-down technique and drain-back technique for direct and indirect SWH systems, respectively. Usually differential thermostats are used to control the system in accordance to the hot water demand with an exception to thermosyphon and integrated collector storage systems.

In the following sections (Section 3.1–Section 3.5), a variety of SWH systems are reviewed and classified in terms of circulation methods and applications. Table 3 summarizes the salient features of different types of SWH systems found in the literature.

Table 3
A summary on studies conducted on solar water heating systems.

Categorization	Investigator(s)	Type of study		Type of analysis		Cost analysis	Collector used	Working fluid	Results
		Theoretical (simulation)	Experimental	Energy	Exergy				
Thermosyphon SWH systems	Close [16]		√	√			FPC	Water	SWH $\eta=38\%$; collector $\eta=43\%$
	DeSa [17]	√	√	√			FPC	Water	collector $\eta=75\%$
	Gupta and Garg [18]	√	√	√			FPC	Water	Water temperature varies 55°–65 °C
	Ong [20]	√	√	√			FPC	Water	Max SWH, $\eta=52\%$
	Sodha and Tiwari [21]			√			FPC	Water	Max SWH $\eta=55\%$
	Kudish et al. [22]			√			FPC	Water	Max SWH $\eta=46–54\%$
	Morrison and Braun [23]	√	√	√			FPC	Water	Water temperature 63 °C and SF=0.65
	Uhlemann and Bansal [24]		√	√			FPC	Water	Pressurized system: thermal $\eta=41–45\%$; collector $\eta=48\%$; Non-pressurized system: thermal $\eta=47–57\%$; collector $\eta=58\%$;
	Hobson and Norton [25]		√	√			FPC	Water	Design a nomogram for thermosyphon SWH
	Shariah and Shalabi [26]		√	√			FPC	Water	Max Solar fraction achieved: Aqaba: SF=0.92 Amman: SF=0.85
	Soin et al. [28]		√	√			FPC	Acetone petroleum-ether	Efficiency of the two-phase collector was 6–11% than similar thermosyphon SWH
	Farrington et al. [29]		√	√			FPC	R-11	SWH $\eta=35\%$;
	Radhwan and Zaki [35]		√	√			FPC	R-11	Efficiency of the SWH varies 60–80%
	Essen and Essen [38]		√	√			FPC with heat pipe	R-134a, R-407C, R-410A	Detailed temp. distribution and cumulative collector efficiencies were determined
	Chien et al. [40]	√	√	√			FPC with heat pipe	Alcohol	Best charging efficiency of the SWH is 82%
	Chen et al. [41]	√	√				FPC with heat pipe	Alcohol	Proposed SWH $\eta=63\%$ (18% higher than the conventional SWH systems)
	Arab et al. [42]		√				FPC with PHP	Water	Collector $\eta=54\%$; water temp. raise 97.7% with PHP
	Yamaguchi et al. [44]		√				Evacuated tube U-pipe	R744 (CO_2)	Collector $\eta=66\%$; heat recovery $\eta=65\%$;
	Ng et al. [45]		√	√			ETHP	Water	Collector efficiency: Thermomax, $\eta=59–66\%$ BSERI, $\eta=58–74\%$
	Redpath et al. [46]	√	√	√			ETHP	Water	By 2D particle imaging velocimetry, the flow regime was determined
	Budihardjo and Morrison [49]	√	√	√			ETC	Water	Measure the optical and heat loss characteristics in a single-ended water-in-glass ETC
ICS systems	Chinnappa and Gnanalingam [54]	√	√	√			Built-in-storage	Water	Total energy collection for the year was 1250 kW h
	Mohamad [55]	√	√	√			FPC storage	Water	Storage tank $\eta=66\%$ and collector $\eta=\sim50\%$
	Schmidt and Goetzberger [56]	√		√		Economically evaluated	Single tube ICS	Water	Annual SF=0.65; annual $\eta=32\%$
	Smyth et al. [59]	√	√	√			Built-in-storage	Water	Overall heat loss reduction up to 20% and thermal energy retention up to 30%
	Garg and Rani [61]		√	√			Built-in-storage	Water	Using insulating cover performance improved 70%
	Kaptan and Killic [63]	√	√	√			Built-in-storage	Water	Mean collector $\eta=50–55\%$
	Chauhan and Kadambi [64]		√	√			Built-in-storage	Water	Collection $\eta=72\%$ for mass flow rate of 75.9 kg/h
	Sokolov and Vaxman [65]	√	√				Built-in-storage	Water	Daily bulk $\eta=53\%$
	Ecevit et al. [66]		√	√			Built-in-storage	Water	For 0.9 m^2 collector area bulk $\eta=57\%$ and 1.9 m^2 collector area bulk $\eta=53\%$;
	Reddy [73]		√	√			Built-in-storage	Water	Water delivery temp. can be achieved over 50 °C with a drop of 1.5–2 °C during nighttime
	Canbazoglu et al. [78]		√	√		Economically evaluated	Built-in-storage	Water	Heat storage capacity with PCM was 2.59–3.45 times higher than conventional SWH system
	Goetzberger and Rommel [79]		√	√		Economically evaluated	Built-in-storage	Water	Annual SF=0.41–0.56; annual $\eta=26–35\%$ for 4 m^2 collector area

	Reddy and Kaushika [84]	√	√	√			Built-in-storage	Water	Solar energy collection η=20–40% at collection temperature of 40–50 °C
	Tripanagnostopoulos and Yianoulis [85]		√	√		Economically evaluated	CPC	Water	Water delivery temperature can be achieved over 50 °C
	Tripanagnostospoulos and Souliotis [87]		√			Economically evaluated	CPC	Water	Two cylindrical tanks were tested; result showed the practicability for DHW system
	Smyth et al. [89]		√	√		√	CPC with modified cusp reflector		Optical η=65% and operating η=35–55%
	Kalogirou [90]	√	√	√		√	CPC	Water	Optical η=65% and system cost 13% lower than convention SWH systems
	Tripanagnostospoulos et al. [91]	√	√	√		√	CPC	Water	Economic analysis showed the system design is cost-effective against the flat-plate SWH system
	Helal et al. [92]	√	√			Economically evaluated	CPC	Water	Max. thermal η=65%
Direct circulation system	Li et al. [94]	√	√	√			ETC	Water	Established a heat transfer model of all-glass vacuum tube collector used in SWH
	Walker et al. [95]	√				Economically evaluated	ETHP	Water	System efficiency 34% for the commercial building
	Chong et al [96]	√	√			√	V-trough reflector	Water	Optical η=70.54%
Indirect circulation System	Chaturvedi et al. [97]	√	√	√			FPT	R-12	COP=2.5–4.0 (30–70 Hz frequency range)
	Hawlader et al. [98]	√	√	√			Air collector		COP (system)=6.0; η (air-collector)=0.77;
	Chyng et al. [99]	√	√	√			Tube-in-sheet type	R-134a	COP=1.7–2.5 (year round); T_{water}=57.2 °C;
	Kuang et al. [100]	√	√	√			FPC	R-22	COP (monthly avg.)=4–6; η (collector)=0.4–0.6;
	Li et al. [101]	√		√	√		Aluminum plate	R-22	COP (seasonal)=5.25 η (collector)=1.08; ε_{system}=21%; T_{water} =50.5 °C;
	Hepbasli [102]	√		√	√		FPC	Water-antifreeze mixture	ε_{system}=44.04%; COP_{system}=0.201; ε_{DSWH}=14.53%;
	Huang et al. [103]	√		√			Tube-in-sheet type	R-134a	COP (HP-mode)=2.58; COP (hybrid-mode)=3.32;
	Guoying et al. [104]	√	√	√			Cu–Al spiral-finned tubes	R-22	COP (monthly avg.)=3.98–4.32; T_{water}=55 °C;
Air systems	Sakai et al. [106]	√	√	√		Economically evaluated	Evapora-tor coil	R-22	Solar fraction=30%; saving of electric consumption=6 kW h/day
	Morrison et al. [107]	√					Fan–coil evaporator		COP (annual)=2.3 (accounted for 56% annual energy savings)
	Ito and Miura [102]	√	√	√			FPC	R-22	13% reduction in energy consumption
	Zhang et al. [109]		√	√			Evapora-tor coil	R-22	COP(winter)=2.61 (T_o=0 °C); COP(summer)=5.66 (T_o=35 °C); COP(spring/autumn)=4.8 (T_o=25 °C);
	Ji et al. [110]		√	√			Evapora-tor coil	R-22	Mode-1: WH: COP (avg.)=4.02; Mode-2: WH: COP (avg.)=3.42, 3.25, 2.52, 2.00 (for T_o=31, 25, 15, 4.5 °C)

Kalogirou [14] classified solar energy systems used water heating application into five different categories: (a) thermosyphon systems, (b) integrated collector storage (ICS) systems, (c) direct circulation systems, (d) indirect water heating systems, and (e) air systems.

3.1. Thermosyphon systems (passive)

This is a passive system (illustrated in Fig. 3) that works on the principle of density difference to transport heat energy. Potable heat transfer fluid (i.e., water) is heated by a solar collector and the natural convection drives the water from the solar collector unit to the hot water storage tank unit. Water becomes less dense due to solar heating and expands according to the temperature rise. Hot water is circulated to the storage tank, and the relatively cooler water from the bottom of the tank is circulated to the solar collector device. This flow is dependent on the duration of sunshine, since it aids density variation which in turn affects the flow of water. To reduce pipe friction, a larger pipe diameter is recommended rather than the normal size (2–3 in. diameter). Usually, connecting lines are kept at an angle to prevent the development of larger air bubbles that would resist the flow of water. Also, the solar collector–inlet is connected to the bottom of the storage tank to avoid reverse flow. In situations, where the collector working pressure is less than the direct supply of city water, suitable pressure reduction valves are used. Usually an auxiliary heater is included to augment the heating process of a SWH, in particularly when used in solar adverse regions [15]. Although, it is not commonly used in the other parts of the world, in European and North American regions, a double tank SWH storage system is used.

Numerous analytical and experimental studies have been intensively carried out on the thermosyphon SWH systems by several researchers and the significant studies are reported in this paper. Close [16] developed a mathematical model to predict the heat gain in a thermosyphon driven SWH system with no draw-off during the hours of operation. This model was validated with the experimental data. In order to numerically evaluate the performance of a solar collector integrated to a SWH system which was subjected to the load removal, DeSa [17] introduced a simplified lumped parameter model to predict the water temperature at the collector outlet. Close's analysis was further investigated in detail by Gupta and Garg [18], Ong [19,20], and Sodha and Tiwari [21].

Gupta and Garg [18] initially predicted the thermal performance of domestic SWHs for the natural circulation mode of operation, under no load conditions. Solar collector's efficiency factor in terms of the shape of the absorber surface and the material's thermal specifications were incorporated in their model. The radiation intensity as well as ambient temperature was also harmonically analyzed. Ong [19,20] in his first performance study on SWH used a "finite-difference method (FDM)" to predict the average water temperature and the water flow rate. However, the measured experimental data were contradictory to the theoretical predictions. Hence, the model was modified by taking into account of the experimental conditions and used the FDM to predict the gain in the temperature at a given time step. Their model was further revised by taking into account of the fin efficiency, collector plate efficiency, and heat loss coefficient of the collector plate. The simulated values agreed well with the measured data confirming the validation of the model. Using the formulation developed by Ong, Sodha and Tiwari [21] analyzed the performance of thermosyphon system, using explicit expressions instead of FDM. The results show that it is possible to predict the performance of SWH system accurately using simple explicit equations.

Kudish et al. [22] adapted a common laboratory practice, such as a constant level device, to measure the thermosyphon flow as a function of thermosyphon head and water inlet temperature. A standard efficiency test curve was drawn based on thermosyphon flow data and confirmed that their method can be used to test solar collectors which operates in thermosyphon circulation mode. Instantaneous solar collector efficiency as a function of time was also predicted and analyzed. Unlike the conventional vertical storage tank used in SWH, Morrison and Braun [23] used a horizontal tank and studied the numerical operational characteristics and compared with the conventional ones. Their results showed that an optimum result could be achieved when the daily collector flow volume approximately equaled the daily hot water consumption volume. However, their results showed that horizontally placed tank did not perform well compared to the vertically positioned tank.

Studies have also been carried out to identify the advantages of a pressurized tank compared to the conventional non-pressurized type. Uhlemann and Bansal [24] performed a comparative study between a pressurized SWH system and a nonpressurized type (Fig. 4). Based on the theory developed by Close [16], performance of this system was evaluated. For the identical meteorological conditions, it was found that the efficiency of the pressurized type, and nonpressurized type of SWH was 41% and 47%, respectively. Hobson and Norton [25] identified thermal characteristics, and operating conditions of thermosyphon SWH, and determined a characteristic thermal performance curve for a directly heated individual system based on a 30 day test data. A perfect fit between the predicted annual solar fraction (SF) and the characteristic curve was obtained. Analysis was further extended to identify precise design parameters of a direct thermosyphon SWH system.

Shariah and Shalabi [26] designed a SWH for Amman and Aqaba in Jordan by taking into account of the geographical conditions.

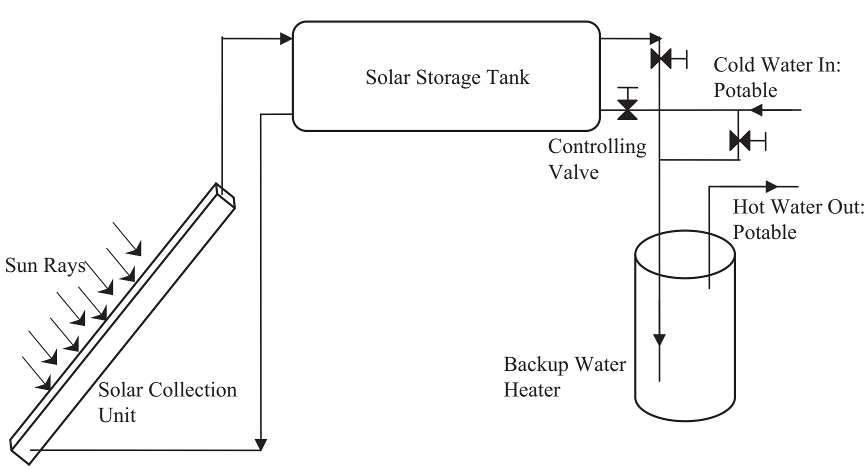

Fig. 3. Basic principle of thermosyphon solar water heating system.

TRNSYS (Transient System Simulation Tool), a very convenient and efficient software package was used to optimize the design parameters which in turn could enhance the SF of the system by about 7% to 25%. Further, it was reported that the optimum values of the design parameters will not only improve the performance, but may also minimize the cost of the SWH system. The study also showed that the variation in design parameters is highly sensitive to mild climate (Amman) than hot climate (Aqaba).

Apart from identifying optimum design parameters, several researches have been conducted to study the effectiveness in operating the SWH system involving 2-phase heat transfer process using various refrigerants, compared to the conventional single phase flow using water. The thermal performance of thermosyphon solar collector, charged with acetone, and petroleum-ether was studied by Soin et al. [27,28]. It was reported the efficiency of the two-phase collector was only about 6–11% which was lower when compared to a direct thermosyphon SWH system. Schreyer [35] investigated the effectiveness of fluorocarbon refrigerant, such as R-11, in the thermosyphon collector for the domestic applications. The experimental results showed that the peak instantaneous efficiency for two-phase refrigerant was higher than using the hydronic fluid.

A similar work was carried out by Farrington et al. [29] on R-11 charged DSWH system installed for a single-family residence. The system could realize an efficiency of about 35%. After a prolonged four year investigation on the hydronic and phase change domestic water heating (DWH) systems, Bottum [30] concluded that with proper installation and maintenance, hydronic system can also yield higher output. However, the refrigerant charged SWH has certain advantages of requiring less maintenance and can eliminate the risk of possible freezing of the working fluids in the collectors. Fanny and Terlizzi [31] developed a correlation "Fanny-Terlizzi correlation" for R-11 driven SWH system. The experiments were carried out indoor using Sun Simulator. The data was further verified with the experimental data that was obtained for outdoor conditions [32]. One of the disadvantages of using refrigerants (which works on closed-loop) is its low efficiency compared to the conventional open-loop system [33]. However, it is possible to increase the efficiency of the SWH systems by charging the collector to the fullest; i.e., the fluid levels in the inlet of the tubes to be nearly the same as the outlet [34]. Radhwan and Zaki [35] depicted the thermal nonequilibrium vapor generation process with fully refrigerant-filled collector tubes (Fig. 5) and showed the dependency of the thermophysical properties (temperature, pressure, and heat flux) of the refrigerant on the circulation flow rate while in phase change. Similarly, Pluta and Pomierny [36] investigated the two-phase thermosyphon DWH system and emphasized on choosing the

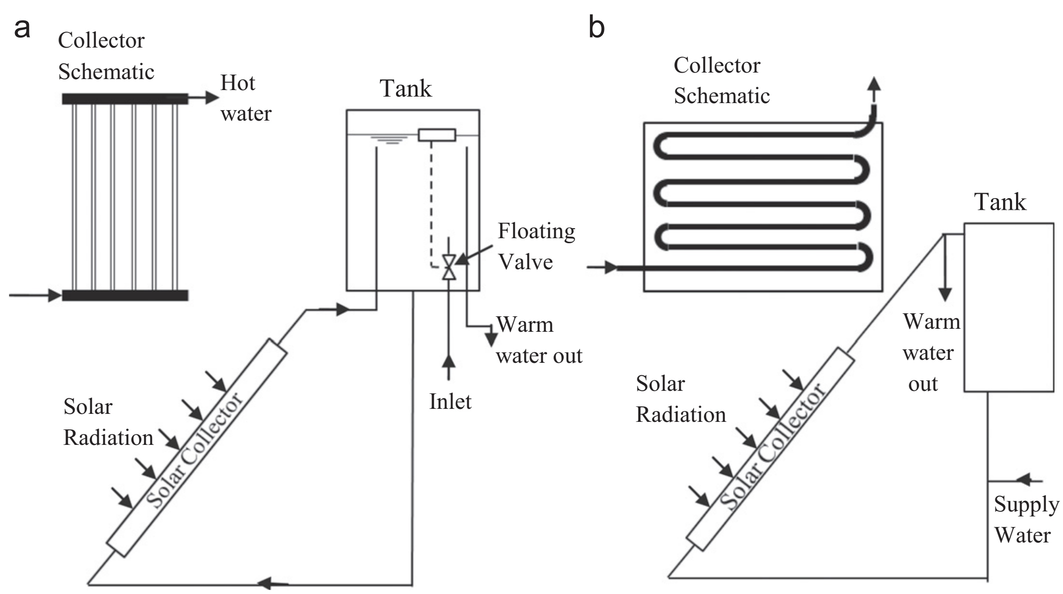

Fig. 4. Schematic diagram of (a) pressurized and (b) nonpressurized domestic thermosyphon SWH system [24].

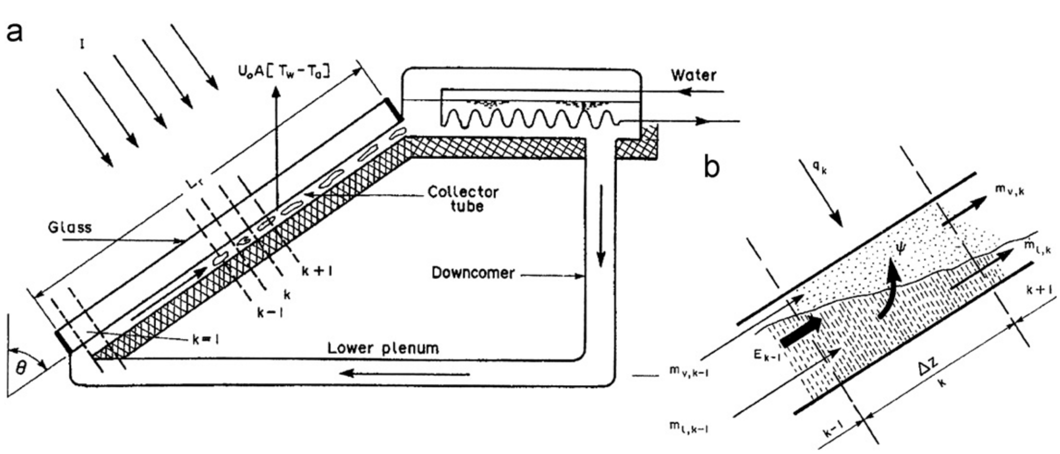

Fig. 5. Thermosyphonic SWH: (a) refrigerant charged two-phase flow; (b) liquid and vapor regions for the unit element [35].

proper heat transfer medium, because it plays an important role in operating conditions of a thermosyphon system.

Apart from water, various other working fluids were tested for its effectiveness on the SWH system performance. Payakaruk et al. [37] investigated refrigerants, such as R-22, R-123, R-134a, ethanol, and water at different filling ratios of 50%, 80%, and 100% and reported its influence on the thermal efficiency of the system. It is reported that the heat transfer characteristics of the system depend on the latent heat of vaporization of the working fluid; the lower the latent heat of vaporization, the higher will be the heat transfer rate. Esen and Esen [38] also studied the thermal performance of closed two-phase thermosyphon heat pipe based solar collector (Fig. 6) using the refrigerants R-134a, R-407C, and R-410A. A similar study was carried out by Chun et al. [39] using different working fluids, such as acetone, methanol, distilled water, and ethanol-distilled water mixer, to measure the performances using heat pipes.

To further identify the optimal filling ratio for the respective maximum solar intensity values, Chien et al. [40] developed a theoretical model and was validated with the experimented data. A charge efficiency of 82% was achieved in their test result which is higher compared to the conventional SWH systems. As a follow up of this reported work, they also analyzed [41] the influence of various heat transfer mechanisms, such as natural convection, geyser boiling, nucleate boiling, and film condensation in the two-phase thermosyphon SWH process. It was reported that by maintaining two-phase flow, it was possible to minimize heat losses and the system could attain about 18% in its characteristic efficiency. Similarly, the use of refrigerants instead of water as the working fluid in heat pipe based SWH system has also shown to have several merits in terms of effective heat transfer, because of occurrence of the phase-change process.

Apart from using the conventional structure of heat pipes, the feasibility of using extra-long pulsating heat pipes (PHP) having many U-turns with the capillary dimensions has recently been realized into the thermosython SWH systems. Arab et al. [42] constructed such PHP based thermosyphon SWH in order to investigate the performance with various filling ratios of distilled water as working fluid. The configuration having 70% filling ratio performed satisfactorily with heat collection efficiency of about 54% while the only thermosyphon mode without the PHP could reach a maximum efficiency of 31–36%.

Most of the refrigerants that are commonly used are either chloro-fluorocarbon (CFC) or hydro-chloro-fluorocarbon (HCFC) which is known to have a detrimental impact on the environment. On the basis of global warming potentiality (GWP), the European Union has passed legislation approving the phase-out process of refrigerants having GWP more than 150 [43]. Research on natural refrigerants, such as ammonia (NH_3), carbon dioxide (CO_2), air has gained momentum. The study reported that it was possible to effect natural convective flow, when CO_2 fluid is heated to supercritical state, because its density was strongly dependent on temperature and pressure. This was sufficient to affect the water heating process. Experiment [44] showed that it was possible to obtain collector and heat recovery efficiencies about 66.0% and 65.0%, respectively, even when operated in winter period.

Other than a conventional use of the flat-plate or evacuated tube collectors, the use of heat-pipe in an evacuated tube collector is relatively new. Ng et al. [45] have proposed a theoretical model to analyze the performance of evacuated-tube heat-pipe solar collector and the model was validated with experiments. The performance parameters, such as the collector efficiency and the useful energy gain were analyzed and the results showed that within a range of coolant temperatures, they had linear characteristics. An experimental study on heat pipe evacuated tube SWH was carried out by Redpath et al. [46]. The internal heat transfer relationships in terms of normalized Nusselt numbers were calculated and presented using the experimental data. Further, two-dimensional Particle Imaging Velocimetry (2D-PID) was used to visualize the thermosyphon fluid regime. The study reported that the high cost related to the heat-pipe evacuated tube SWH can be minimized by replacing the forced circulation to a thermosyphonic type. Enhancing the convective heat transfer can result in the overall improvement in the thermal efficiency of the thermosyphon type SWH systems. A comprehensive study on different possible heat transfer augmentation techniques were discussed by Jaisankar et al. [47] in the review. Among the various techniques, the effects of different design ratios of twisted tapes (both helical and left–right arrangement) incorporated

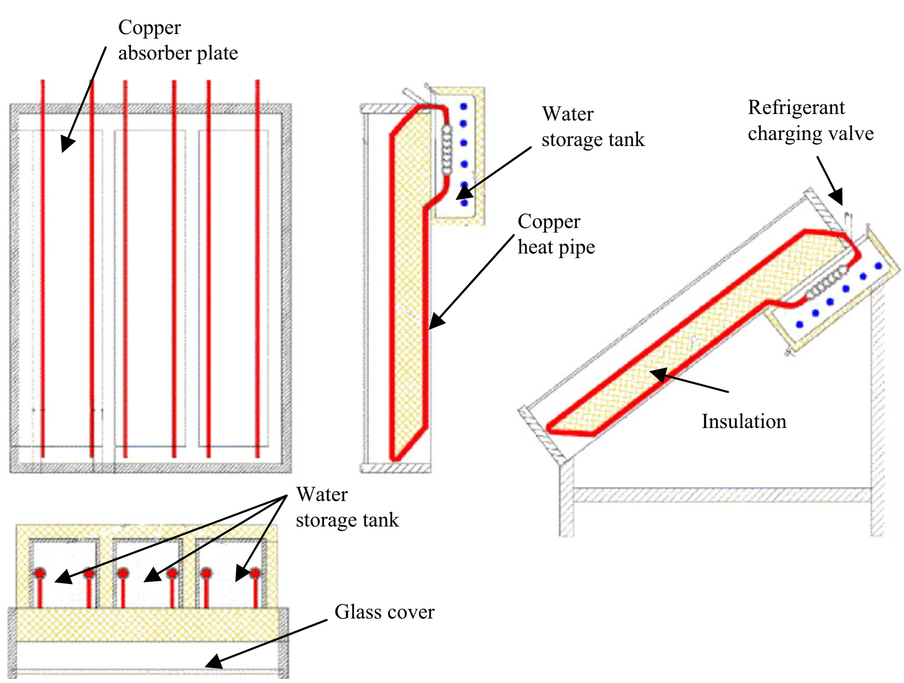

Fig. 6. Schematic diagram of thermosyphon two-phase water heater with the use of heat pipe in a flat-plate solar collector [38].

into the heat exchanger and SWH systems were extensively studied. Ho and Chen [48] introduced internal fins into the most common sheet-and-tube solar collector to increase the effect of convective heat transfer coefficient. Their study summarized the effect of fins attached under various arrayed density in the recyclic operation and concluded that higher collector efficiency could be achieved under optimum parametric design.

Budihardjo and Morrison [49] simulated a water-in-glass evacuated tube thermosyphon SWH device to measure the optical and heat loss characteristics in a single-ended tube. This system is also popularly referred to as the “wet-tube concept”. The investigated system incorporated pressure tubing inside an all-glass evacuated tube system that is commonly used in solar energy market. One of the drawbacks is that it is applicable only for low-temperature application, because of the fact that the fluid is circulated in the glass tube which cannot endure high pressures. In order to examine the influence of collector tilt-angles on the thermal performance of water-in-glass tubes SWH, Tang et al. [50] have tested two identical experimental set-ups having tilt-angles of 22° and 46°, respectively.

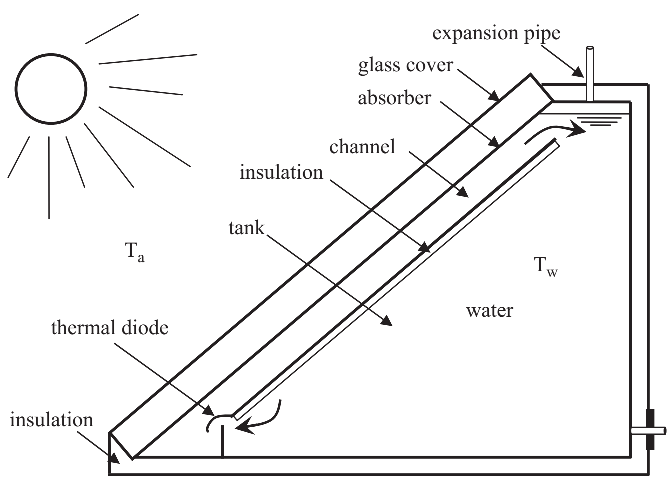

Fig. 7. Schematic diagram of ICS solar water heating system designed by Mohamad [55].

Their results showed that the solar collector tilt-angle has significant influence on the daily solar heat gain, but insignificant on the daily solar thermal conversion efficiency.

There are also many studies conducted with the introduction of heat exchanger into the thermosyphon SWH systems. A detailed theoretical analysis along with the experiments have been done incorporating coiled copper tube as internal heat exchanger placed inside the storage tank by Koffi et al. [51]. Their results showed a 58% collector thermal effectiveness with a hot water temperature of 85 °C which was tested in the West African meteorological region. Huang et al. [52] introduced different types of thermosyphon flat-plate SWH with a mantle heat exchanger. Experimental results have shown that the mean daily efficiency of SWH using a mantle heat exchanger can reach up to 50%. This reported value may be lower than that of thermosyphon flat-plate SWH without heat exchanger, but higher than that of an all-glass evacuated tubular SWHs.

3.2. Integrated collector storage systems (passive)

Unlike the conventional SWH system in which a collector acts as an absorber of sunlight, the ICS system utilizes both the collector as well as the storage tank as an absorber to collect solar radiation. In most cases, the entire exterior part of the reservoir acts as an absorber. However, these systems are subjected to heavy heat losses, especially during non-sunshine hours. Several measures, such as selective absorber surface coatings, insulating materials, and a single or double glazing glass covers have been used to reduce the heat losses. A few other techniques were also attempted to culminate the heat loses: movable protection cover, insulated baffle plate, and utilizing phase change material (PCM) inside the storage tank. Researchers have also attempted to use transparent insulating materials for the appropriate exposed parts. Further, to reduce the heat losses, the storage tank was operated on thermal stratification modes, by drawing the hot water from the top of the storage tank and cold water inlet to the bottom of the tank.

Numerous studies on the design and thermal performance improvements of ICS system SWH are presented in the literature. Technological development in the ICS SWH systems have comprehensively discussed by Smyth et al. [53]. Several design parameters,

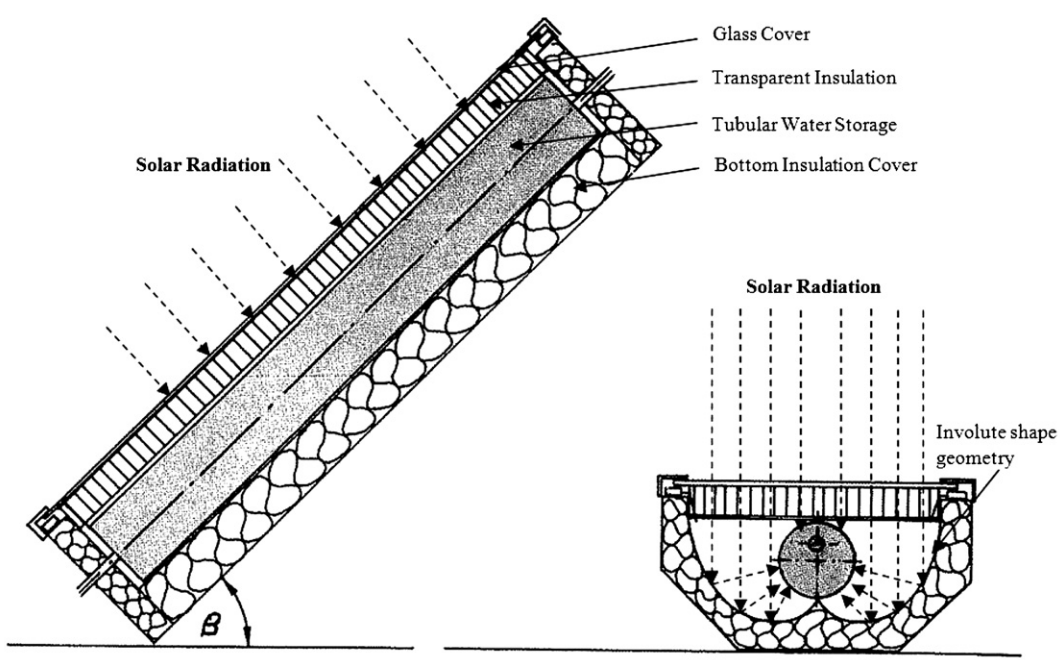

Fig. 8. Schematic diagram of the cross section of ICS system investigated by Schmidt and Goetzberger [56].

such as storage tank design and its' orientation, methods of glazing, insulation, reflectors, use of PCM in the storage tank, use of baffle plates, and this influence on optical efficiency and thermal performance have also been detailed in their study. The first draw-off rectangular shaped ICS SWH system was introduced by Chinnappa and Gnanalingam [54]. The system contained about 13 m length metallic coil (diameter = 7.5 cm) inserted in the wooden box with the bottom being insulated and the top being provided with a double paned glass cover. The study reported that, the system performed well providing hot water (around 50 °C) about 30–50 gallons, on a clear sunny day.

Similar to the above work, an easy-to-manufacture integrated SWH system was studied by Mohamad [55] in which a thermal diode was used to avoid the reverse flow of hot water during the night time (Fig. 7). The results proved that the thermal diode significantly reduces the heat losses. Various studies have suggested that tubular storage system is better than rectangular storage system, since it is more pressure resistant, and be able to connect water mains directly. For use in colder regions, such as Freiburg, Germany, an effective ICS system combining the tubular-shaped storage tank with a reflector of involute geometry was proposed by Schmidt and Goetzberger [56]. Their system is schematically depicted in Fig. 8. The thermal performance of a SWH system involving more than one storage tank connected in series was analyzed by Sodha et al. [57]. A correlation for the general design method of ICS systems to evaluate the annual solar fractions of the systems was developed by Panico and Clark [58]. To mitigate the heat loses to the surrounding environment, a novel built-in-storage vessel design was proposed by Smyth et al. [59]. Their experimental results reported a 20% heat loss reduction by the system. A similar work utilizing a heat exchanger was attempted by Kumer and Tiwari [60]. Fig. 9 shows the schematic of the system in which a heat exchanger plate was incorporated to augment the heat transfer. ICS systems are generally employed for low cost system applications. Garg and Rani [61] designed a rectangular storage tank with a nighttime insulating cover to maintain the water temperature above 40 °C. In order to enhance the performance further, a baffle plate was used inside the absorber tank [61,62]. Results showed that, if the system with baffle plate and is covered with insulation during night time, the system can supply hot water up to 55 °C in the early morning hours. Kaptan and Kilic [63] also worked on a tubular design provided with a baffle plate and confirmed that the collection efficiencies can be significantly improved by optimizing the baffle plate and the insulation thickness of the storage tank.

Similar to the above discussed work, Chauhan and Kadambi [64] worked on an inexpensive SWH having a rectangular storage tank of 70 l capacity. The water in the storage tank was in direct contact with the absorber plate which was placed on the top of storage tank. Four different modes of operation, such as (a) flow aided by a pump, (b) thermosyphonic flow, (c) draw-off water at water temperature around 50–60 °C, and (d) continuous flow of water over the absorber plate at the rates of 38 kg/h, 60 kg/h, and 76 kg/h, were tested. When operated under natural convection mode, the system could attain a thermal efficiency around 50–53%, with hot water attaining a temperature of about 50–57 °C. Instead of rectangular geometry storage tank Sokolov and Vaxman [65] and Ecevit et al. [66] introduced a triangular shaped storage tank in an ICS system. Results have shown that it is possible to achieve a bulk efficiency of about 60%, which is much higher than a conventional thermosyphon system (35%) [67].

The use of phase change material in the water storage medium has been reviewed in detail by Shukla et al. [68]. An ICS system incorporated with latent heat storage was investigated by Prakash et al. [69]. During the effect of sunlight, water gets heated and eventually heat is transferred to the PCM stored in the form of capsules at the bottom of the tank. During the period of no sunshine, and the time of withdrawal of hot water from the storage tank, the PCM releases energy by changing its state from liquid to solid that keeps the water warm.

Paraffin wax (MP 54 °C) was used as thermal energy storage medium [70]. To further improve its efficiency, a reflector was utilized to effect solar energy collection. The system could ensure good recovery of hot water supply over a 24 h cycle, with an efficiency of about 60%. Galenen and Brink [71] and Kumer [72] also used Paraffin as the heat storage element. Reddy [73] also tested transient performance of an ICS water heating system, using Paraffin as PCM. PCM was stored in a rectangular enclosure provided with fins to augment the heat transfer. The study shows that maximum water temperature, minimizing the heat losses. The temperature of water without any fins was measured to be 50 °C with a drop of 1–2 °C during nighttime. However, with an optimal nine-fin configuration, the maximum water temperature

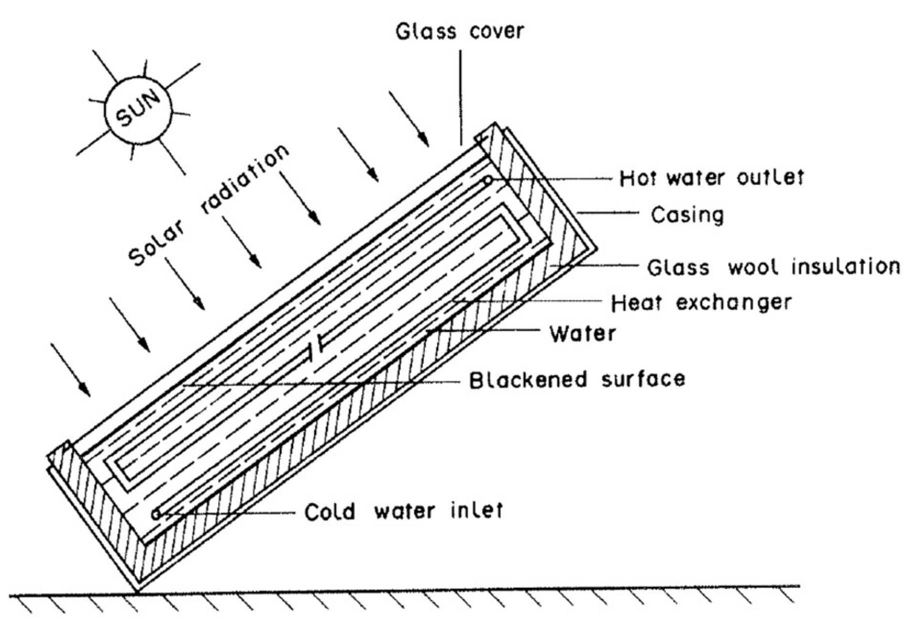

Fig. 9. Built-in-storage solar water heater incorporated with heat exchanger plate designed by Kumer and Tiwari [60].

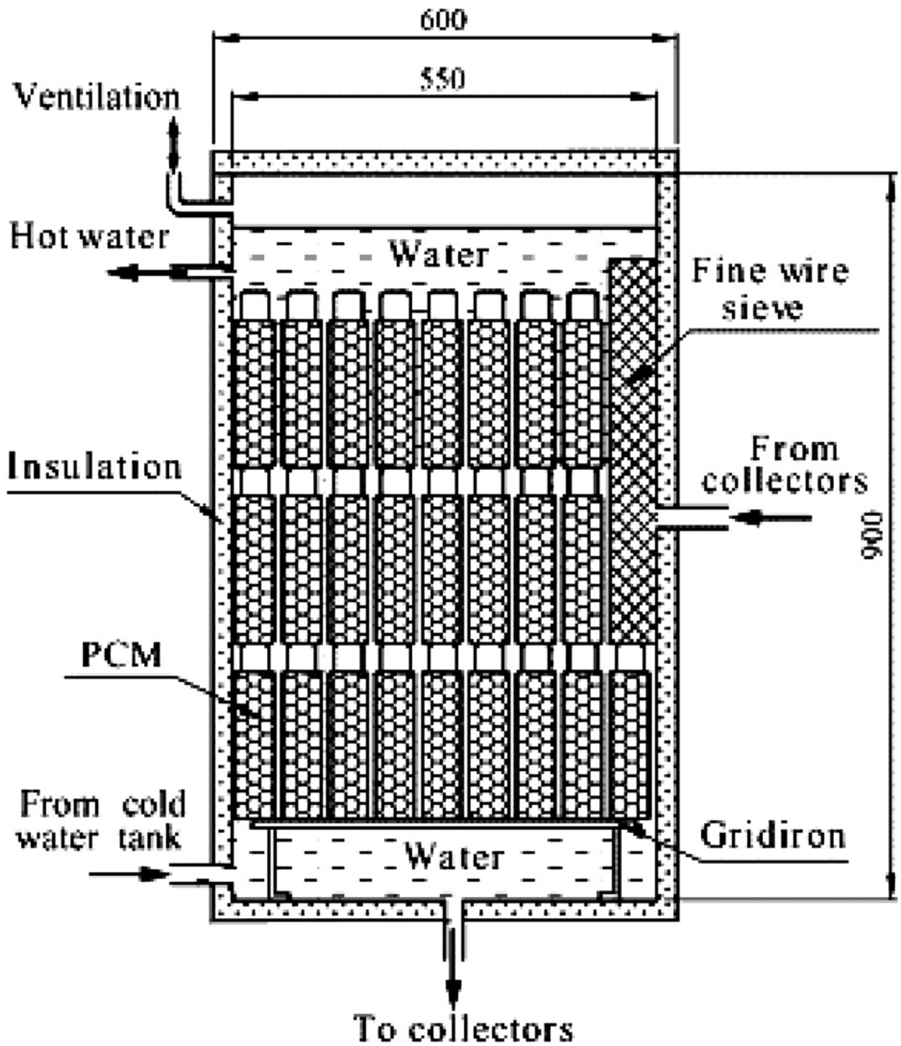

Fig. 10. Cross-sectional view of heat storage tank combined with PCM was designed by Canbazoglu et al. [78].

could reach up to about 83 °C which is comparatively higher than the other ICS configurations. Several other phase change materials, such as ammonium alum ($NH_4Al(SO_4)_2 \cdot 12H_2O$, MP 95 °C), fatty acid, palmitic acid, and stearic acid with melting temperature varying 50 °C to 70 °C have been used for ICS water heating system [74–77]. Canbazoglu et al. [78] compared PCM-charged SWH systems with that of the conventional SWH systems with no PCM. PCM-filled polyethylyne bottles were set in their storage system in three rows. The cross-sectional view of the system is shown in Fig. 10. Various hydrated salt-PCMs, such as zinc nitrate hexahydrate ($Zn(NO_3)_2 \cdot 6H_2O$), disodium hydrogen phosphate dodecahydrate ($Na_2HPHO_4 \cdot 12H_2O$), calcium chloride hexahydrate ($CaCl_2 \cdot 6H_2O$), and sodium sulfate decahydrate (Glauber's salt–$Na_2SO_4 \cdot 10H_2O$) were tested. The variations in water temperatures at the midpoint of the water storage system with respect to the collector outlet temperatures were investigated. Without drawing-off the hot water during night, the system could attain about 46 °C. Results were compared with the conventional SWH system and found that the hot water production and the accumulated heat in the SWH system were roughly 2.6–3.5 times higher in case of with the PCM-charged system.

Numerous studies have been conducted to enhance the thermal performance of an ICS device by incorporating transparent insulation material to the appropriate sections of the solar collector and storage tank [79–83]. Goetzberger and Rommel [79] have summarized different types of transparent insulating materials that could be used over the absorber/collector plate (Table 2). The listed works utilized evacuated-tube and integrated-collector-storage system, and was tested using indoor sun simulator. Reddy and Kaushika [84] also worked on the temperature insulation materials, but experimental studies were conducted under outdoor conditions and it was possible to attain the storage efficiencies around 20–40%.

Apart from using a conventional flat-plate collector integrated to an ICS device concentrated collectors have also been used to assist the operation of ICS device. Several other significant studies have been carried out on the stationary compound parabolic collector (CPC) solar concentrating devices. The use of ICS type solar systems of horizontal cylindrical shape with the aid of stationary asymmetric CPC curved mirror envelop were designed (Fig. 11), constructed, and tested by Tripanagnostopoulos and Yianoulis [85]. What made this work unique was that a hot air trap was created between the absorber surface and the reflector to suppress the thermal losses. Their results showed that it was possible to attain storing water temperature to about 50 °C, even during low solar radiation (~600 W/m^2). They further modified the system by incorporating two series connected cylindrical storage tanks placed horizontally in asymmetric CPC reflectors. These low cost and long-lasting systems were designed to operate efficiently using two inverted cylindrical surfaces by mitigating thermal losses. The geometrical shape of inverted cylindrical surface used in DSWH systems are illustrated in Fig. 12.

The horizontal and vertical positioned ICS storage systems with symmetric CPC and involute reflector troughs were tested by Tripanagnostopoulos and Souliotis [87]. A comparative assessment was made between the CPC and involute reflector troughs in terms of daily mean efficiency and results have shown that CPC reflectors could achieve higher mean daily efficiency (37–60%), while involute troughs could achieve higher efficiency only at low working temperature conditions. To minimize heat losses in an ICS system, Smyth et al. [88,89] have proposed a modification. That is, to place 2/3rd of the storage vessel in a 'W' modified concentrating cusp and the remaining part to be kept outside the reflector cavity with proper insulation. With such modification, it was possible to retain 60% of the collected energy for a continuous period of 16 h of non-solar periods.

To further improve thermal performance of the CPC integrated ICS device, Kalogirou [90] proposed a built-in-storage system comprising of two cylinder storage tanks. Later, some design improvements were made by Tripanagnostopoulos et al. [91] to attain an efficient and low cost ICS system. Both single and double cylindrical horizontal tanks, constructed in symmetric and asymmetric truncated CPC reflector troughs were tested. Two cylinders connected in series showed better water temperature stratification

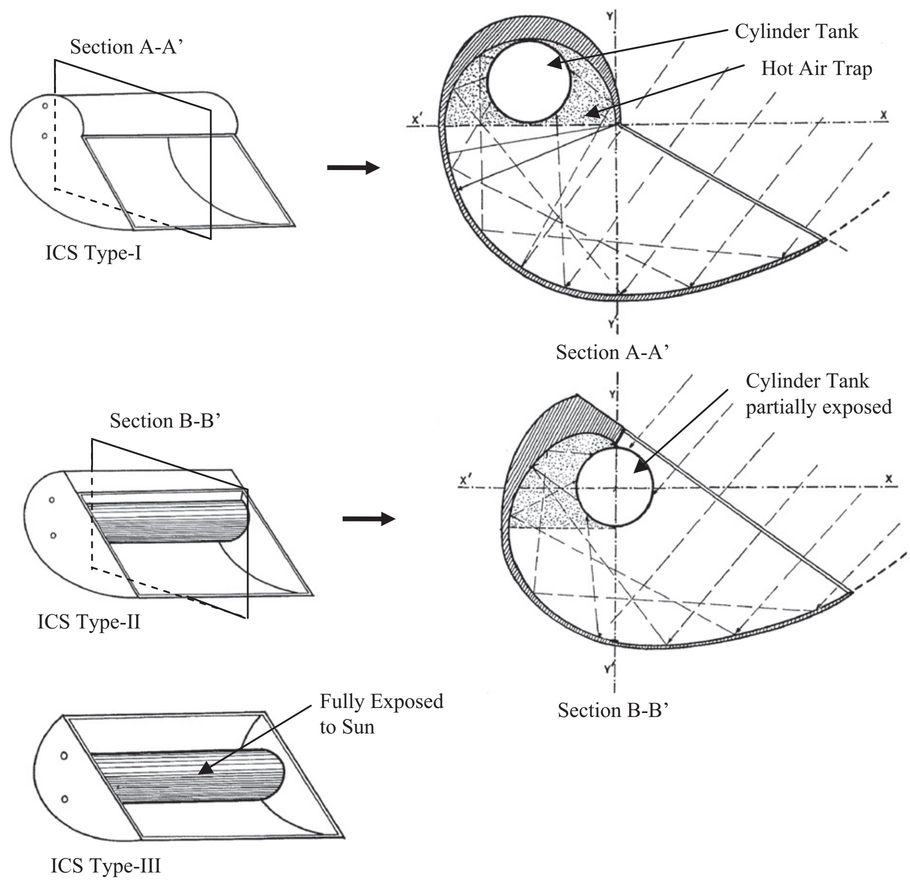

Fig. 11. Three different types of Integrated Collector Storage (ICS) system designed by Tripanagnostopoulos et al. [85].

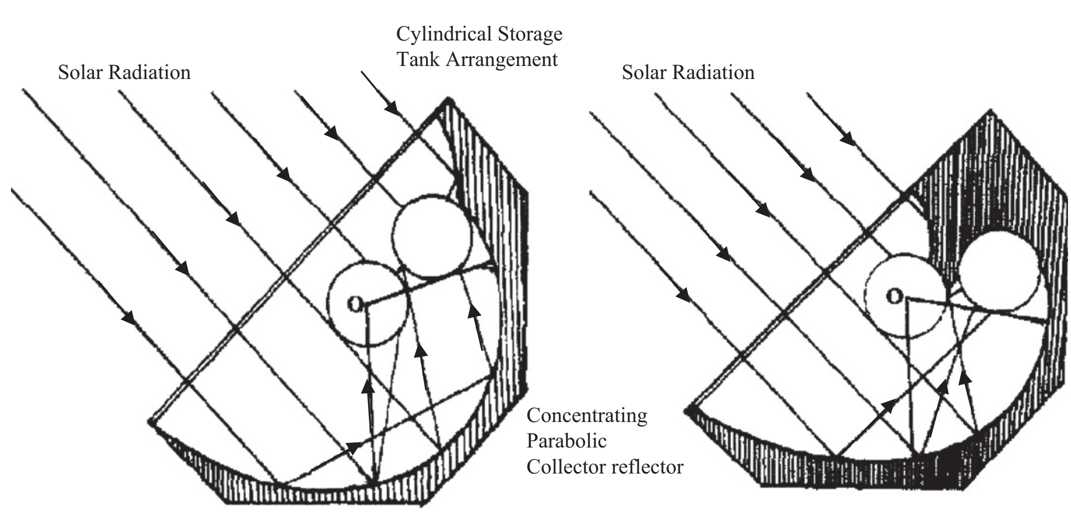

Fig. 12. Cross sectional view of the asymmetric CPC reflected two cylindrical storage tank ICS system proposed by Tripanagnostopoulos et al. [86].

and the asymmetric CPC reflectors have contributed for thermal loss reduction. One of the highlight of this study is its simplicity in design and cost-effectiveness. Cost reduction of these ICS systems are due to the use of iron oxide glazing, economical matt black coating for the absorber surface, and stainless steel sheet (or aluminized Mylar) for the reflector surface. The involute shaped geometry of the parabolic reflector was further designed using a single cylinder tank with a reflector including three parabolic branches by Helal et al. [92] to make the ICS system more compact and less costly with improved performance for a medium-sized family.

A new type of inverted absorber ICS SWH placed in a tertiary cavity of CPC reflectors incorporated with a secondary tubular shaped reflector was tested by Smyth et al. [93]. Different transparent baffles were positioned in the ICS cavity and the results showed that the incorporation of baffle plates could not only improve the optical efficiency, but also increase the thermal retention at a rate of 59.3% by suppressing the convection losses.

3.3. Direct circulation systems (active)

Unlike thermosyphon systems, direct circulation systems require a pump to circulate water from storage tank to the collector to get heated. The hot water flows back to the storage system and is ready for the end-user. The pump is usually controlled by a differential thermostat that regulates water at the top header by a sufficient margin to the bottom of the tank. A check valve prevents the reverse circulation to avoid nighttime thermal losses from the collector. The collectors can be positioned either above or below the storage tank as pump is used to activate circulation. Direct circulation system is generally used only under situations when freezing is not a concern. Sometimes, water from the cold storage tank or city water supply can be used directly into the system. Care should be taken when quality of water is hard or acidic, in a direct circulation system since it would result in scale deposition which in turn may cause clogging or corrosion of the collector tubes. Direct circulation systems more commonly employ a single storage tank which is with an auxiliary heater. However, in few case-studies, two-tank storage systems have been used as well.

During the inevitable situations, when the direct circulation system has to be employed, to operate in adverse weather conditions (where ambient temperature can go below 0 °C) certain modifications are introduced in the design of SWH system to overcome the freezing issues. One such modification is to operate the direct circulation system in drain-back mode. Generally, a differential controller integrated pump is used to circulate water from the storage tank to the solar collectors. A drain-down valve provides the freeze protection function. While turned on by the controller, the valve isolates the solar collector inlet from the storage tank outlet. At the same time, the differential controller opens a valve that permits water to drain away from the collector. In order to drain water out from the bottom of collectors, a vacuum breaker is installed at the top of each collector to allow the air circulation.

For well-known reasons, such as, low cost and superior anti-freeze performance, all-glass vacuum tube collectors are commonly used in direct circulation SWH system. In the past few decades, majority of vacuum tube collectors were used for domestic water heating purposes. As expected, the performance of vacuum collectors is higher than flat-plate collector due to low convection heat loss from the absorber. The heat transfer model evaluates the performance of all-glass vacuum tube collectors incorporated in a direct circulation system was developed by Li et al. [94]. This simplified model takes into account of natural circulation in single glass tube as well as forced flow circulation in the manifold header. The flow equations were obtained by analyzing the friction losses and buoyancy forces inside the tube. A positive agreement was observed between the predicted and computed collector outlet temperatures, and the deviation was within 5%. The system schematic is shown in Fig. 13.

Walker et al. [95] designed and installed a direct circulation SWH system (Fig. 14) at the Social Security Administration's Mid-Atlantic Center in Philadelphia. Evacuated-tube heat-pipe solar collector of 36 m^2 net absorber area was employed to energize the storage tank. The simplicity in design and low erection cost made the system attractive to be implemented in commercial buildings. Unlike conventional systems, in this system the incoming water was preheated in the recirculation loop.

Due to the fact that evacuated tube collector generate high temperatures beyond 100 °C, it might be a point of concern when operating in regions where the ambient temperature and solar radiation availability is high during summer. To prevent thermal losses from the evacuated tube, a high temperature switch can be employed. This control switch can overcome the abovementioned issue. To overcome the two temperature extremes, such as overheating in summer and freezing in winter, air can be used as the working fluid in the circulation tubes rather than using water directly. A fan is used to mobilize the air through the flow distribution tubes and the concentric air-to-water heat exchanger delivers the heated water to the horizontal storage tank.

Apart from what was previously discussed, different types of solar energy collecting devices flat plate collector, evacuated tube collector, ICS system, and concentrating collector devices, a relatively new V-trough SWH system is also available in the commercial market. An easy to manufacture and cost effective V-trough SWH employing direct circulation mode was analyzed by Chong et al. [96]. By combining solar absorber with a V-shaped trough reflector, the thermal performance of the SWH was substantially improved. The test was carried out with and without glazing and insulating materials. It was reported that the prototype could achieve an optical efficiency of 71% with a maximum outlet water temperature to 82 °C and 67 °C for with and without insulation, respectively.

3.4. Indirect water heating systems (active)

Indirect systems of SWH utilize two circulation loops to effect heating: (a) the closed-collector loop and (b) the open storage tank loop. Usually, the heat transfer fluid is circulated within the closed-collector loop, to gain the heat and is then passed through a heat exchanger where heat is transported to the potable water that flows in an open loop to the storage tank. There are several different types of working fluids used in the closed loop, such as water, refrigerants, and anti-freeze mixtures. The heat exchanger can either be an internal system (placed inside the water storage tank or outside of the storage tank) or as an external system. An expansion tank integrated with a pressure relief valve is used in the closed circulation loop system. In the pressurized system, the tank is provided (an additional expansion tank) to have a control on temperature and pressure of the working fluid. However, for the unpressurized system, the tank is provided to release the pressure when required to vent.

There exists numerous works [97–104] related to the indirect mode of SWH systems and some significant investigations are discussed in this section. A variable capacity direct expansion solar-assisted HP system for the DWH purpose was tested by Chaturvedi et al. [97]. The system used a bare solar collector acting as an evaporator for the heat pump system. The system was tested for the widely varying ambient conditions, and accordingly the compressor speed was varied through a variable frequency drive. The observational results showed that the coefficient of performance (COP) of the system can be enhanced extensively by reducing the

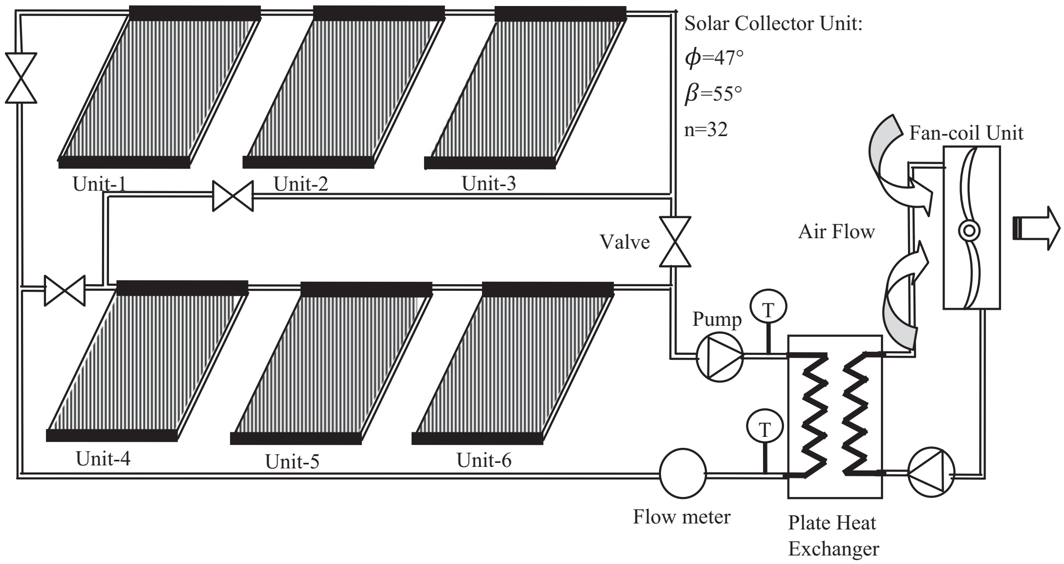

Fig. 13. Schematic diagram of the experimental set-up developed by Li et al. [94].

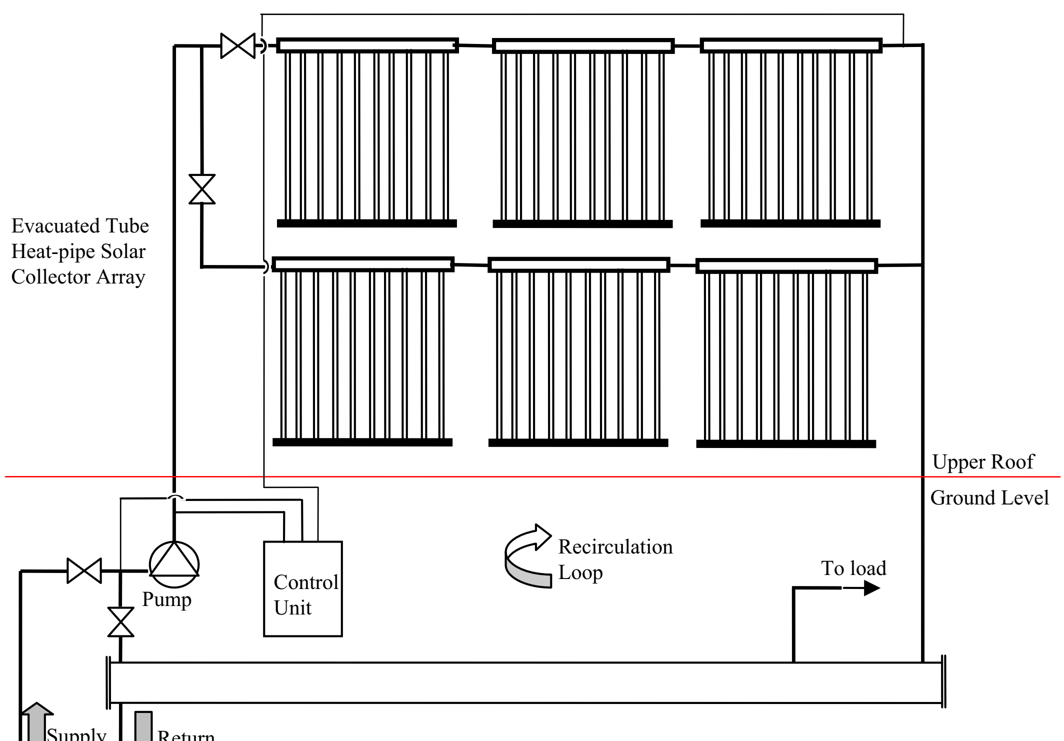

Fig. 14. Schematic diagram of a recirculation loop applied to the SWH systems of commercial building [95].

speed of the compressor when the ambient temperatures are higher. Hence, such systems perform better in summer compared to winter.

Hawlader et al. [98] designed, fabricated, and tested a combined solar-assisted HP dryer and water heater that had been examined under the ambient conditions of Singapore. The system consisted of a variable-speed reciprocating compressor, solar collector as evaporator, water storage tank and, an air-cooled condenser. To assess the influence of different variables and the performance of the system, a Formula Translation (FORTRAN)-aided simulation program was developed. The system performance with and without an auxiliary water heater, was compared in terms of the performance parameters, such as SF and COP. The COP values of the predicted and experimental studies were reported to be 7.0 and 5.0, respectively. Similarly, the SF was 0.65 and 0.61, respectively.

The performance of an integral-type solar assisted heat pump (ISAHP) water heater was carried out by Chyng et al. [99] and the schematic of the modeled system is shown in Fig. 15. Simulations were performed based on the assumption that, except the storage tank, all other components are at steady-state. The model agreed well with the experimental data and the predicted results were within 10% of the measured data.

Analytical and experimental studies on a direct-expansion solar-assisted heat pump (DX-SAHP) water heating system (Fig. 16) were conducted by Kuang et al. [100]. The system comprised of a 2 m^2 bare flat-plate collector was used as an evaporator as a part of the

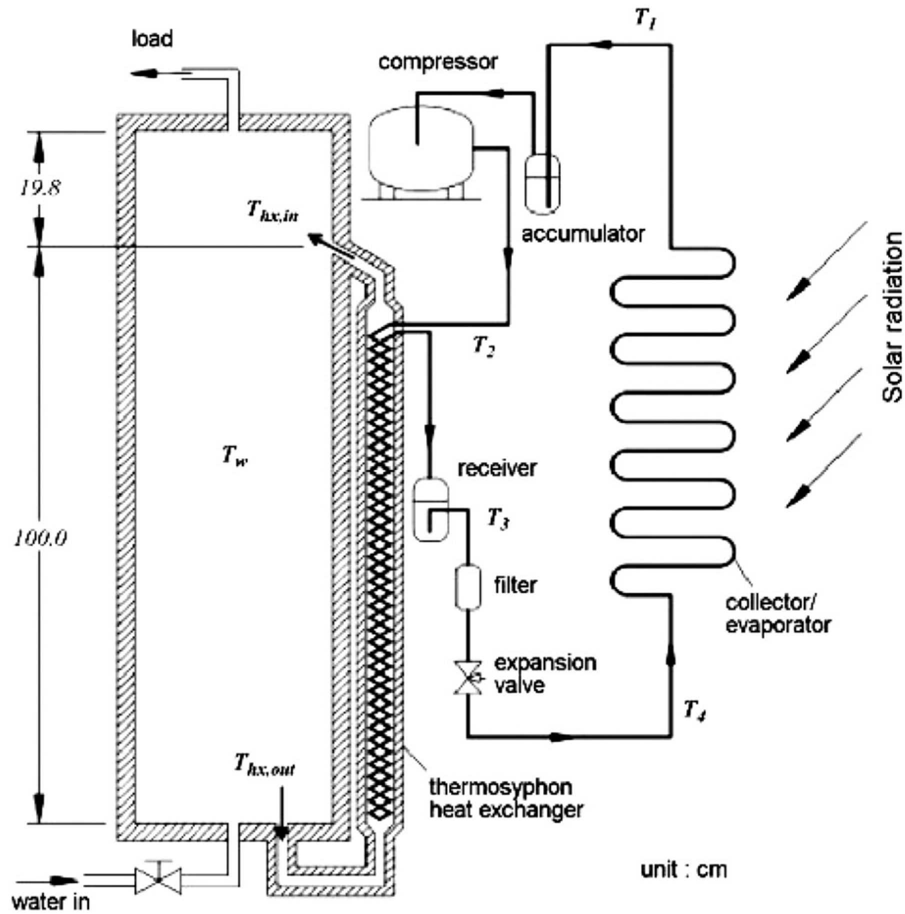

Fig. 15. Schematic diagram of integral-type solar-assisted heat pump (ISAHP) system [99].

refrigerant cycle. The long-term thermal performance of the system was predicted by a simulation model. The results have shown that monthly average COP ranged from 4 to 6, while the solar collector efficiency varied from 40% to 60%. A similar work was carried out by Li et al. [101]. The DX-SAHP system comprised of 4.2 m^2 solar collector as evaporator area, a 0.75 kW hermetic compressor of rotary type, 150 l water storage tank with a copper coil of 60 m length submerged into the tank, a thermostatic expansion valve, and R-22 refrigerant was used as the working fluid. The system was shown to heat 150 l of water a day to a temperature of 51 °C, when the maximum solar radiation received at noon was about 955 W/m^2. The exergy analysis on each of the element of the DX-SAHP water heating system, identified that most heat losses occurred in the compressor, followed by the collector, and the condenser. To further enhance the thermal performance (for the SWH system as well as all the other components), additional methods were also suggested. Hepbasli [102] also carried out exergy analysis to evaluate the performance of a solar-assisted domestic hot water tank coupled with ground-source heat pump (GSHP). Along with the GSHP system components, a solar collector of 12 m^2 surface area and a water storage tank was integrated to it. Results proved that, it is possible to attain 14.5% efficiency for residential SWH system and 44.06% when the entire system is taken into account.

Apart from heat pumps, heat pipes were also utilized for water heating application. Huang et al. [103] worked on heat pipe solar-assisted conventional heat pump (HPSAHP) water heating system. The performance of the combined solar heat pipe collector and conventional HP were examined to calculate the overall COP of the system. When solar radiation was low, the system operated in HP mode. However, during the clear sunny days, the heat-pipe mode operated independent of electrical energy input, to higher thermal efficiency. The designed and constructed prototype was tested outdoors and the schematic is shown in Fig. 17. The results showed that the COP of the hybrid-mode of operation could attain as high as 3.32, and as such its performance was higher by about 29% compared to the HP mode of operation.

Guoying et al. [104] carried out a numerical study to evaluate the operational performance of a solar air-source heat pump (SASHP) water heater (Fig. 18). This system was specially designed which utilizes a flat-plate solar collector being provided with spiral-finned tubes to collect energy both from solar radiation, as well as from the surrounding air. For the given meteorological conditions of Nanjing, China, the theoretical results showed that the designed SASHP water heater of 150 l capacity could efficiently heat water up to 55 °C.

3.5. Air systems (active)

Unlike water or other refrigerants, air has also been used as working fluid, for its unique advantages. Compared to the conventional SWH system, air can be used as a working fluid even during freezing weather conditions, is non-corrosive, and requires only low maintenance requirements. However, the system is generally large and requires considerably large space for air handling unit. A typical arrangement of a solar air heating system incorporated with a pebble bed storage unit is illustrated in Fig. 19. Fans and dampers are incorporated to aid the system operation. The heat gained by the air in the collector duct is released through a heat exchanger to aid domestic hot water supply of up to 80 °C.

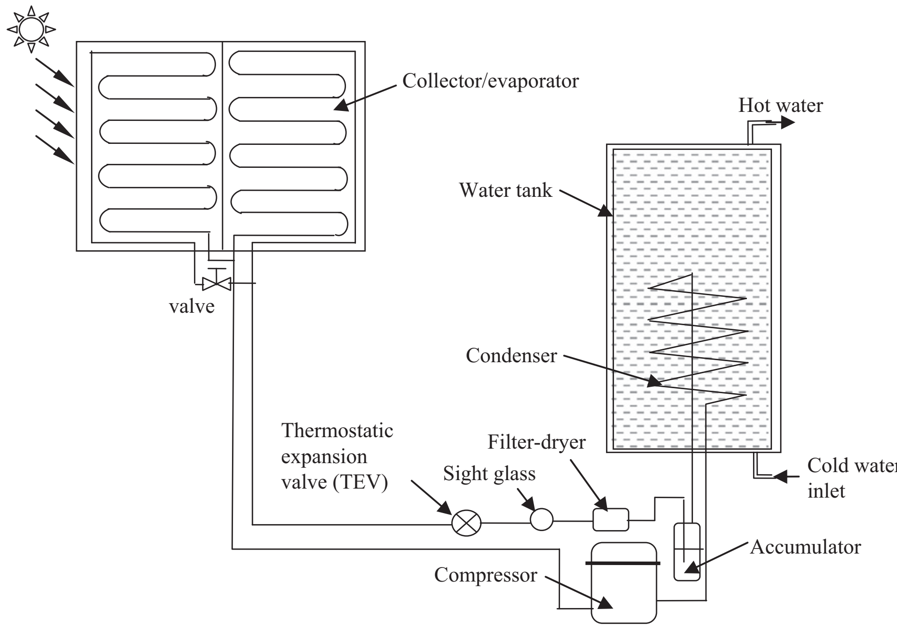

Fig. 16. Schematic diagram of DX-SAHP water heater presented by Kuang et al. [100].

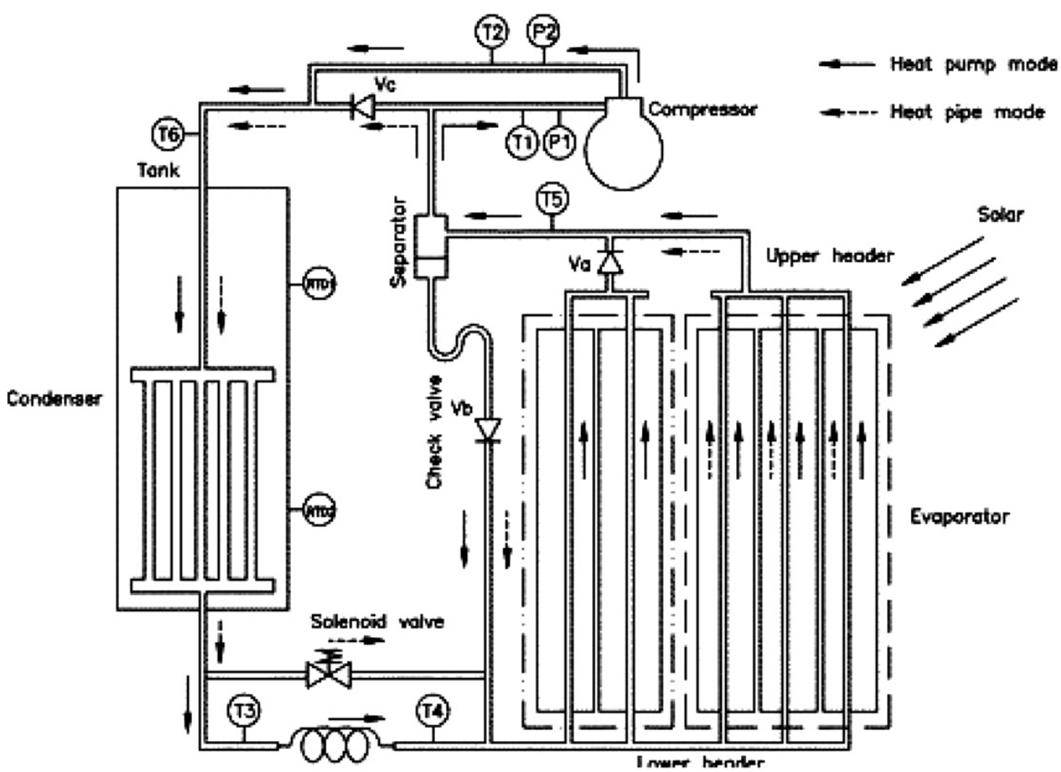

Fig. 17. Schematic diagram of heat-pipe solar-assisted heat-pump system presented by Huang et al. [103].

A major drawback of the air systems is that air has low heating capacity and its performance deteriorates further when the ambient temperature is very low. Research has been carried out to overcome the disadvantages that are inherent to air assisted HPs to certain extent. Sekai et al. [106] studied a specific HP system that could overcome the aforementioned problem. An air-source HP was designed to operate on a HP cycle and was provided with an auxiliary heater to meet the demand during insufficient solar radiation. The HP mode of operation was activated during day-time and the study showed that, the solar energy enhanced the total electrical energy savings and the need for reverse cycle defrosting operation was eliminated. A common form of air-source HP water heater as a packaged product is comprised of a water-cooled condenser, a compressor, and a fan-coil evaporator. Condenser may either be separated from the storage tank through which water is pumped from storage tank and placed at the top of the unit or a wrap-around coil on the wall of the storage tank. An air-source HP of this kind (Fig. 20) was evaluated by Morrison et al. [107] for its seasonal performance and annual load variation of the system and was reported

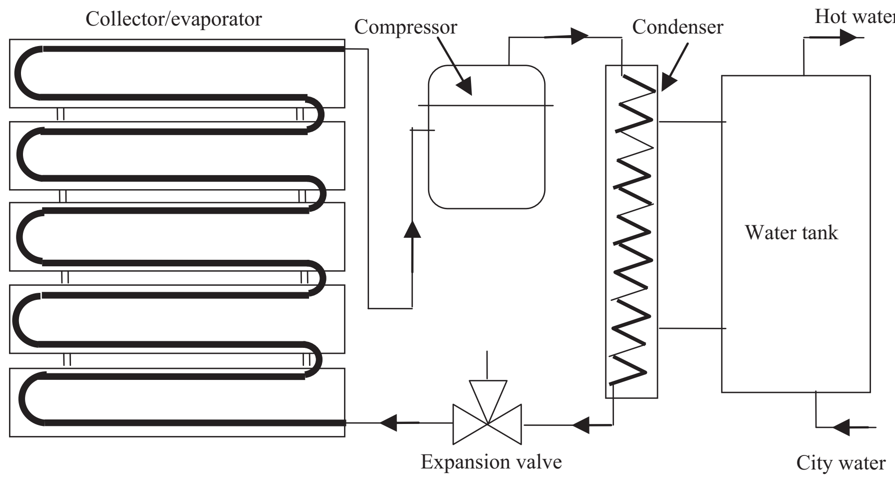

Fig. 18. Schematic diagram of SAS-HPWH designed by Guoying et al. [104].

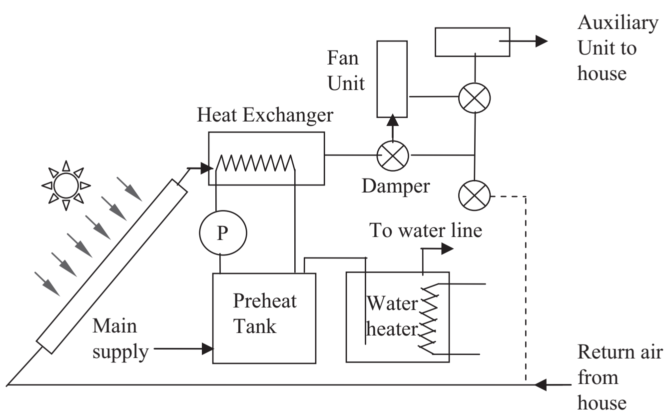

Fig. 19. Schematic diagram of standard air system configuration [105].

that the system could attain an yearly average COP of 2.3 (accounting for 56% annual energy savings). Although the tested COP is significantly lower than other conventional types of SWHs or solar-assisted HPs, the installation flexibility of these systems have a scope in solar-adverse regions. Currently air-source HP products are commercially available and are used in regions that encounter harsh weather conditions.

To improve the performance of air assisted heat pump water heating systems, studies have been carried out by Ito and Miura, utilizing dual heat sources: air and water. At steady state conditions, for the heat pump, when the temperature of a specific source was greater than the sum of the temperature of its degree of superheat and the evaporation temperature of the other (alternative) heat source, heat would be absorbed from both heat sources at the same time. This resulted in a higher evaporation temperature as well as higher COP compared to a single heat source system [108].

Zhang et al. [109] worked on optimization of air source HP water heating system. This system included a HP, a water storage tank, and connecting pipes. The energy gained in the evaporator from the air source is transported via a Rankin cycle to release heat to the cold water. This system employed a rotary compressor to run the thermodynamic cycle to heat the water from its temperature up to a pre-set water temperature of 55 °C.

A novel combined air-conditioning and a water heating system was introduced by Ji et al. [110]. Such split-type air-conditioner unit under out-door conditions could affect both space cooling and water heating, simultaneously. But the air-to-water HPs for water heating are not popular, because of its high initial costs, and unreliability in operation.

Apart from the above discussed solar water heating systems, literature [140,111,112] shows that photovoltaic (PV) panels were also utilized to demonstrate water heating. Though it has some merits such as not requiring freeze protection and simple installation, these systems are not popular because of the current cost and the PV modules. Similarly, studies on photovoltaic thermal collectors have been used to affect water heating. Recently, Xu et al. [113] have analyzed experimentally a low-concentrating photovoltaic/thermal collector integrated heat pump system. Fixed truncated parabolic concentrators were used to reflect solar radiation on the photovoltaic cells, and R134a was used as refrigerant in the HP mode. It was reported that the system could provide the hot water up to 70 °C with an average COP of 4.8 in summer period.

4. Economic aspects of solar water heating systems

4.1. Techno-economic evaluation of SWH systems

The potential of any renewable technology is dependent on the proper assessment of planning and promoting the system among the end-users. A method to evaluate the market potential for domestic water heating has been presented by Voinvontas et al. [114]. The method has been based on a geographical information system (GIS) in the domestic sector of Greece. The model took into consideration the parameters associated with geographical variability that influenced solar radiation and power requirements for the specified area. The size of the population and the number of families greatly influenced the energy demand in residential energy uses. The above discussed model provides some special insight into the energy savings and profits that could be obtained from a large-scale deployment of domestic water heating systems. The model takes into account of two main financial factors; power generation cost, and the net present value of the investment. For Greece, based on the current installation of domestic water heating systems ($\sim 2\times10^6$ m^2 collector area), it has been estimated an energy saving of about 1200 GW-h/yr. The study further shows that, it is possible to increase energy savings to about 3169 GW-h/yr, if the estimated 75% of homes install the SWH systems. Currently, this model is helpful to analyze the variation in energy demand with the time discrepancies of solar radiation. However, it was restricted only to the domestic sector and did not account for the variation in load. A typical domestic hot water load pattern has been analyzed by Mutch [115].

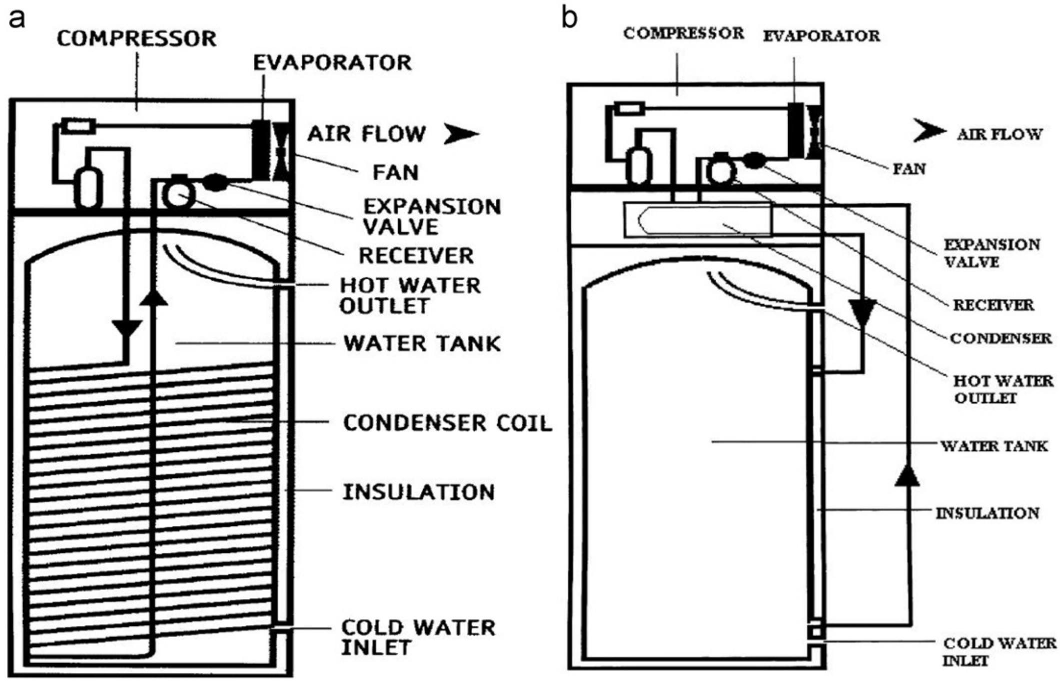

Fig. 20. Air-source heat pump water heater (a) with wrap-around condenser coil, and (b) with external condenser [107].

As expected the hot water demand in the morning and evening hours was generally higher than the rest of the day. To support the large fractions of these loads, water heated by solar energy must be stored one day prior to the consumption. Minor variations of time discrepancies on load patterns do not have any major impact on the performance of DWH systems. However, variations in peak demand during weekend closures of commercial buildings may have a significant influence on water heater performance and its optimal design parameters.

The techno-economic evaluations play an important role in establishing a strong market strategy for solar water heating systems and also persuade necessary information for energy policy decisions. Chandrasekar and Kandpal [116] have developed a comprehensive nomograph to determine the potential number of households who can use water heating systems in India. Factors, such as the availability of shadow-free sunshine hours, space availability, practical awareness of system operation, cost of the SWH system, financial constraints, and motivation plays a role in the establishment of water heating systems in the residential buildings. A simple framework for financial evaluation of SWH systems was also developed which took into account of net present value of the system, the benefit to cost ratio, internal rate of return, and the payback period. Based on a thorough investigation, the study reports that, the operation and maintenance cost of the system as well as capacity utilization plays as key factors in the penetration of this solar water technology in the domestic market.

The above discussed model presented inputs for assessing the utilization of SWH systems in India. Using some of these inputs, Pillai and Banerjee [117] developed a methodology to estimate the potential for SWH systems for India, by taking into account of both micro and macro level inputs as shown in Fig. 21. The methodology was end-user based and hence, the end uses of the target area initially identified and classified on the basis of application sector. The potential was then estimated for each type of end-use based on its hot water use pattern and other micro level factors. As a case study, the developed methodology was implemented to a target residential area of 2 sq. km which included hospitals, hotels, and nursing homes. The study reported that with installation of SWH systems ($\sim$1700 m^2 collector area), it could lead to a potential savings of 1.1 million kW-h of electricity per year. The estimated technical potential, economic potential, and market potential (with no auxiliary heating) are 1700 m^2, 1540 m^2, and 300 m^2 of collector area, respectively. The proposed framework is generic in nature and provides accurate information about SWH system required for any specific area and henceforth, policy makers could use this as a tool to track and promote SWH systems nationwide.

Another simple method to evaluate the effectiveness of SWH systems is to assess the energy savings by the product of the SF and the numbers of SWH integrated buildings. Denholm [118] has published a detailed on the technical potential of SWH to reduce fossil fuel use and green house gas emissions in United States. Several technical factors were investigated in evaluating the feasibility of SWH systems: (a) the orientation of house roofs, (b) the minimum size of roofs, (c) the fraction of shadow covering the solar collector, and (d) the capability of supplying hot water according to the demand. It was also reported some other related nontechnical factors: (a) the cost estimation of SWH, (b) aesthetics, (c) local building codes, (d) percentage of buildings in use by tenants, and (e) ordinances. The study has reported the current technical potential of SWH in US is estimated to about 1 quad (1.055×10^{18} J) of primary energy savings per year. To implement the cost-benefit analysis more effectively, Pan et al. [119] proposed the concept of number of effective solar days and effective solar radiation (ESR) instead of using the total annual solar radiation parameter which may overestimate the amount of energy benefits. ESR calculation was based on the tap water temperature and the solar insolation for each region of Taiwan to figure out the applicability of SWH. This model estimated the ratios of ESR to total annual solar radiation in the range of 82–89%, and the payback periods from 6 to 15 years, for different geographical regions of Taiwan.

The popular f-chart method [120] and the demographic data for a target region can also be used to assess the estimated power savings due to the installation of domestic SWH systems. Financial profits can be estimated using economic indices and profit potential of the manufacturing may be estimated by comparing all of the economic costs and benefits regarding SWH. These costs included material and labor costs as well as taxes. Market prices

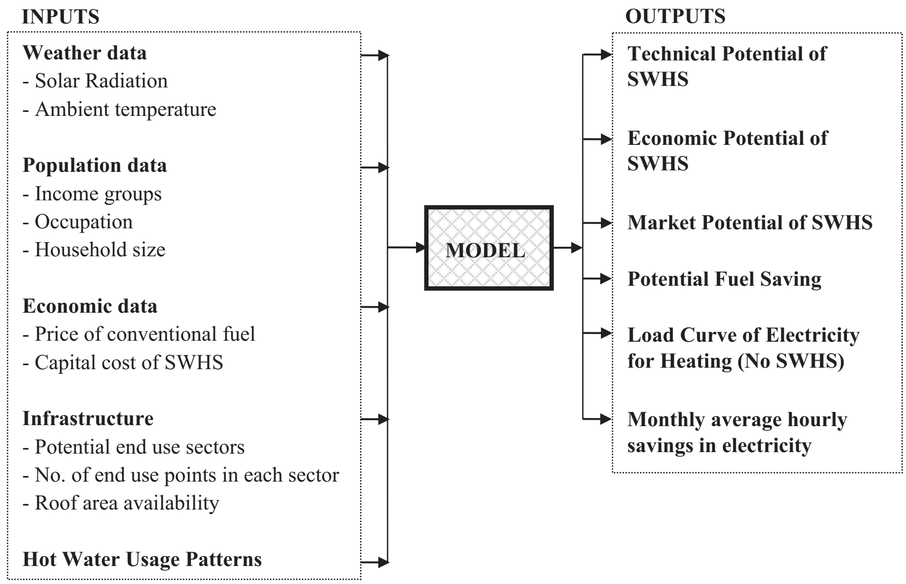

Fig. 21. Input and output parameters for modeling the potential approximation of solar water heating system [117].

of SWH product generally depend on the size of the system, its brand name, and the place of purchase.

4.2. Cost reduction trend in SWH systems

Due to technological feasibility and economic viability among various other applications, SWH systems are one of the most popular systems of utilizing solar energy as the energy source. There exist numerous low temperature applications for various end-uses, such as residential hot water production, space heating/cooling, commercial buildings, hotels, schools, swimming pool heating, industrial process heat, solar-assisted district heating, desalination, and crop drying. SWH technologies are already well developed and can be easily marketed at considerably low prices. A comparison of cost and typical characteristics of SWH systems used by US and China market is presented in Table 4. From the energy utilization perspective, Xiaowu and Ben [122] conducted an energy analysis based on "Three Procedure Theory" in which three sub-procedures, such as conversion procedure, utilization procedure, and recycling procedure are closely related to each other. To provide a good assessment of saving cost of the system and to increase the efficiency of the domestic-scale SWH, an exergy analysis of the system was also conducted. This helps to figure out exergy losses and identify the most inefficient component of any SWH system. The study reported that the storage tank is the weakest unit and suggested to maintain stratification in the tank, to minimize losses.

Apart from the domestic uses, hot water and pressurized steam are used for industrial applications. The cost of the industrial SWH system varies depending on the thermal capacity, storage convenience, and pressure requirement for the system. Another growing market for SWH is the commercial building sector. Many government policies are now in place to promote solar units for common household purposes, such as water heating, space heating, and cooling applications. To meet such dependencies, solar energy driven products need to be manufactured in a proportionate rate. However, adopted policies have the goal to achieve 20–30% of the potential uses in future [123].

Total cost of SWH system which includes the costs associated with manufacturing to the installation stage is influenced by various factors, such as costs related to engineering expertise, labor for installation, cost of solar thermal collectors, structural costs of mounting racks, plumbing supplies, pumps, data logger, controller, and other space related costs [124]. Government rebate subsidies also have an impact on the market penetration of SWH systems. According to the US Energy Policy: 2005 (Section 1335), tax credit amounting to 30% of the total purchase amount of qualified SWHs [125]. This Credit also applies to cover associated costs with equipment and cost of labor related to installation, piping, and wiring.

The Social Security Administration (SSA) and general services administration (GSA) in Philadelphia switched their auxiliary heating component of SWH system from using fuel oil and natural gas to solar radiation [95] mainly due to high gas prices. As an alternative approach, this cost-effective design could provide advantages of avoiding additional tanks and piping for the preheating system of flat-plate collectors. The use of evacuated-tube collectors made the system possible with a recirculation loop of SWH at the roof of the building. Modifying the existing system with the reheating of water heating system could be yet another alternative way to implement cost effective retrofits of SWH systems on existing commercial building. This moderation could in turn increase the market penetration of this type of SWH system. ASHRAE reported the Active Solar System Design Manual [126] that presents the details about this reheating approach.

4.3. Factors influencing SWH economics

Following typical phases of any technology development, economic aspects also plays a major role in dictating the marketability of the product. Economic performance of the SWH system depends on several important factors, such as (a) the insulating materials and the method of insulation, (b) materials used to construct, (c) the effectiveness of bonding between collector tubes and fins, (d) thermal conductivity of tubes and fins, (e) corrosion resistance of the exposed parts and water contacts, and (f) the life span of the entire system in various climatic conditions. Another important factor that influences on the performance of SWH system is the water quality. Especially in the urban regions of the developing countries where quality of water is not maintained, major issues are encountered in terms of scale formation in the connecting pipes and the collector system, resulting in poor performance. Solving such issues demand some modifications to the SWH system. An external heat exchanger with a heat transport medium could resolve this problem. In the case of a large scale SWH system, a

Table 4
Comparison of costs and other general characteristics of SWH market between US and China [121].

Characteristics	US market	China market
Typical installed cost (domestic, 2–4 people)	$5,000–10,000	$300–1,000
Most common technology	Indirect (with pump)	Thermosyphon (no pump)
Tank capacity	80 gal	30–50 gal
Collector sizes	~50 square feet	~20 square feet
Backup system	Conventional electric/gas	Electric heating element
Quality	Highest, SRCC certified	Low, many not certified and shorter system life
Typical installation	Collectors on pitched roof, indoor tank, complex design, building not designed for SWH, limited SWH experience, high labor costs.	Collectors and tank on the roof (flat or pitched type roof), simple system, experienced installers, low labor costs.
Market volume	30,000 installs/year	6000,000 instalations/year

number of collectors need to connect in series to energize the storage tank. Hot water production capacity of above 3000 l/day of such systems are usually connected by an array of collectors in series with considerable length of pipes which require a driving pump to circulate the heat transport medium rather using the thermosyphon mode of operation [127]. Another cost-effective approach is to install DSWH systems by integrating the collector and water supply piping with the initial floor-plan of new homes to be constructed. A collective approach can be adopted by installing a community SWH facility which would supply the demand of a group of houses. Optimization of solar collector area to the storage tank capacity for a hybrid SWH was studied by Misra [128]. It was reported that the use of auxiliary heater inside the storage tank causes large amount of heat loss due to the fact that the hot water storage tank needs to maintain a large volume of water at constant delivery temperature. Reducing the auxiliary energy consumption could improve the economics of the system. Therefore, it was recommended to provide auxiliary heater at the load point.

In order to obtain techno-economically feasible standardized water heating systems, it is important to evaluate the viability of the chosen SWH system design. Such studies will serve as one of the promotional measures in deploying them in the market. The need for viability studies of DSWH systems has been detailed by Srinivas [127] and has presented an exclusive viability study on the development and dissemination levels of DSWH systems in Indian households. Various factors and sub-elements related to the dissemination barrier of DSWH systems which impede the widespread use among the end-users were analyzed. Srinivas suggested four simple dimensions along with its characteristic features to overcome the barrier and to make such systems economically viable: technical dimension, economic dimension, commercial dissemination dimension, and social and behavioral dimension. Among these, technological barrier was pointed out as one of the major barriers which included the efficiency of SWH system, quality of elements used, product life cycle, and reliability of components, method of sophistication used, and ease of running (installation, maintenance, and operation). Besides this, economical dimension also influence the viability of the system which is largely dependent on low energy cost, subsidies of market competitive items, and cost of operation/maintenance.

The net savings of a SWH system is also dependent on its size. SWH systems though popularly employed to meet the domestic hot water supply; they are also utilized to serve the hot water demand in the industrial sector. A capacity of 8000 kW-h thermal SWH plant was modeled and installed by Nagaraju et al. [129] to supply a demand of 110,000 l/day of about 85 °C for the egg powder plant. Solar collector having an exposed area of 2560 m^2, four storage tanks (each having storage capacity of 57.5 m^3), and distribution pumps were integrated together to serve as a SWH system. It was reported that the annual net savings of fossil fuel consumption was about 78%. A similar study was carried out by Muneer et al. [130] to learn the prospectus of introducing SWH systems in the textile industries. An economic analysis of the proposed SWH system was carried out to find the monetary viability of the system and it was reported that the payback period is about 6.7 years.

In order to improve the performance of PV panels as well as to improve the economics of such system, PV-thermal systems were introduced. A photovoltaic/thermal (PV/T) solar system provide the generation of electricity as well as heat energy simultaneously. Water is used as coolant to absorb the waste heat from the PV panel, and this waste water (coolant) could be utilized for domestic purposes. In typical warm climate regions, liquid PV/T systems are particularly useful for domestic hot water production. An economical evaluation of a PV/T water heating system was carried out by Sok et al. [131] for the Northern part of China. Though the objective was noble, the study reported that such systems are not economically viable due to the inherent high costs of the PV panel. An estimated annual generation of 790 kW-h thermal energy and 100 kW-h electric energy were compared with the current low energy priced other conventional SWH systems and reported that in the current market, the hybrid PV/T could not make enough economic savings. Thermal energy output from a PV/T system can easily be replaced by an 85% efficient gas water heater considering an equivalent amount of energy consumption. However, a combination of lower initial investment, operational costs, higher PV thermal conversion efficiency, and financial support could make the hybrid system attractive. Recently because of a large demographics and the recent limitation of roof space per household, the Chinese government has considered the PV/T technology to be an alternative option and are now showing commitment towards policy development to make the hybrid PV/Thermal technologies cost-effective, which may become economically viable in the near future.

Another collective approach is the “solar combi-system” which supplies space heating and cooling demands along with the hot water production. This system utilizes many small solar collector units connected together in series. A back-up system of non-solar secondary heat source is necessary for the uninterrupted heat services to the connected areas. About 10–60% of the collective hot water and heating requirement can be met in the most part of the central and the northern Europe by employing such system [2]. In many parts of Europe, regional heating and cooling systems use solar energy integrated with the conventional sources. In Germany alone, eight solar-assisted district heating systems were constructed by the end of 2003, which have the prospect to serve 30–95% of total heating and hot water demands per year.

4.4. Installed market structure and related costs of SWH systems

Solar thermal collectors are mainly used for heating water to provide heating or cooling depending on the domestic and industrial

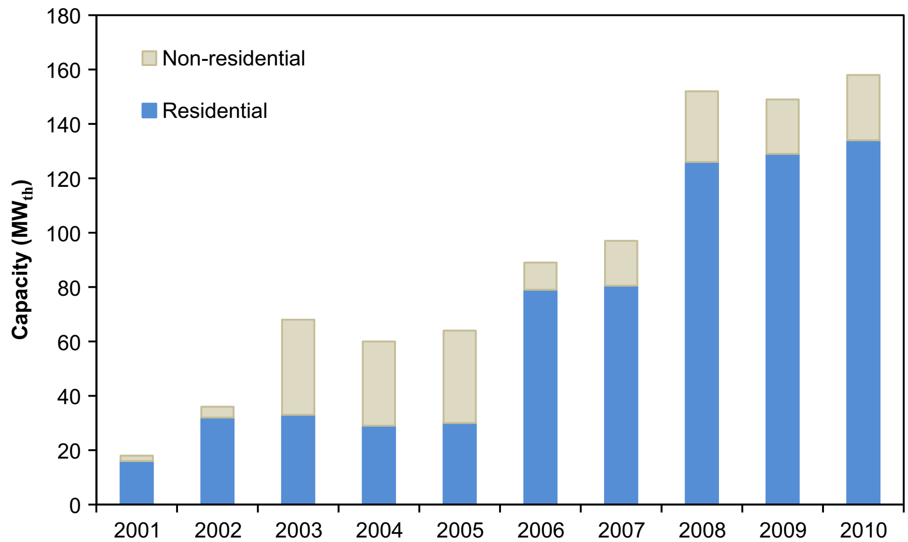

Fig. 22. Annual installed U.S. capacity for solar heating and cooling, 2001 to 2010 [133].

Table 5
Status of the solar water heating systems, characteristics and the energy costs in world market [132].

Application	Typical characteristics	Typical energy costs, (U.S. cents/kW h)
Solar hot water	Size: 2–5 m^2 (household); 20–200 m^2 (medium/multi-family); 0.5–2 MW_{th} (large/district heating); Types: Evacuated tube, Flat-plate	2–20 (household) 1–15 (medium) 1–8 (large)

Table 6
Averaged profile dependent efficiencies measured from different water heating systems [138].

Systems	Average COP (all year around)	ASHRAE 90.2 Draw schedule (Avg. COP)	NREL/BA Draw schedule (Avg. COP)
Standard Electric 50 gal. tank	0.85	0.87	0.83
Solar flat plate differential w/ 80 gal. tank	3.41	3.55	3.29
ICS w/50 gal. tank	1.44	1.63	1.28
Solar flat plate PV pumped w/ 80 gal.	2.43	2.94	2.34
Tankless electric	0.89	090	0.87
Natural gas 40 gal. tank	0.54	0.54	0.55
Tankless natural gas	0.71	0.72	0.70

sectors' requirement. It has been estimated by solar energy industries association (SEIA) and Green Technology Media that SWH installation has increased by 6% in 2010 relative to the previous year solar market in US [133]. Fig. 22 shows the shipment details of solar collectors in US from the year 2001 to 2010. Among the residential installations, pool heating by utilizing solar thermal collectors has increased 13% in US. Approximately 81% of medium-temperature collectors for the year 2008 were used for water heating. The increase in shipment of medium-temperature collectors over last decade is supposed mostly due to the Federal tax credits and state incentives. In 2010, California Solar Initiative adopted new program to increase the number of SWH installations by adopting state rebates. Though this initiative, a customer can reduce the associated capital cost of a typical residential SWH ranging from $2000 to $3000 up to 30% by taking advantages of the initiatives [134]. A global characteristic status of SWH systems and related energy costs are listed in Table 5 for reference.

Morrison and Wood [112] had surveyed and presented a detailed 20 year-progress report which includes various SWH designs on current market trend. The primary exporters of SWHs are Australia, Greece, and USA; most other countries only supply domestic demand. Solar water heaters have two main merits, such as reducing the impact on environment pollution and serving as an alternative replacement to the conventional fuel. Wood and He [135] have illustrated a life-cycle-cost model to evaluate the total cost and benefits of ownership. Both, the power generation technologies, and SWH service life of each component were taken into account. The California Energy Commission [136] had created a comprehensive economic model for SWH devices in collaboration with the solar industry. Based on a conservative lifetime of 10 years, the annual cost for heating water using solar collector ranges between $514 and $527, depending on the energy factor (ratio of useful energy to the energy consumption). The cost of the SWH system also varies depending on the location, hot water load, and utility costs. For low capacity heating, such as pool heating, the installation cost varies from $100 to $2400 per square meter of collector area. However, installation costs for the glazed SWH systems vary from $640 to $1600 per square meter of solar collector area [137]. According to National Institute of Building Science, an installed SWH system against electricity can reduce the water heating bills up to 80%. Based on the life-cycle analysis, the energy independence and security act (2007) estimated the life-cycle of a SWH system is about 40 years.

Florida Solar Energy Center carried out a performance testing on seven types of water heating systems which utilized either solar energy, or commercial energy sources, such as electricity or natural gas. A comprehensive report was published in the 2010 [138] and the results are summarized in Table 6. The reported results indicate that solar flat-plate water heating system of an

80 gallon capacity consumed the lowest daily average energy consumption and performed well with a reasonably higher COP compared to other water heating systems.

4.5. Social impacts and environmental issues

Both environmental and social impacts must also be taken into account while assessing the economic feasibility of SWH systems. In 2011, International Energy Agency (IEA) analyzed at a global level the contribution of solar heating towards CO_2 reduction. It was reported that a significant reduction in CO_2 can be achieved (Fig. 23) by using flat-plate and evacuated tube collectors [139]. National Renewable Energy Laboratory of DOE reported that the technical prospects of SWH in US market is estimated be around 1 quad of annual primary energy savings which in turn results to an annual reduction of approximately 50–70 million metric tons of CO_2 discharge to the atmosphere [118]. Further, the reported annual savings associated to SWH could translate to over 8 billion dollars in retail power costs benefiting the consumers. These savings can avoid the conventional fuel price escalation. Promoting the development of SWH utilization also helps people to convey their concerns about ecological safety. China spends substantial amount of capital on publicity and awareness to improve the SWH penetration into the commercial market.

In addition to other positive effects on the society, the promotion of alternate energy products will help decrease unemployment, increase income, and create more indirect jobs. Table 7 represents the new jobs created by solar thermal application of leading countries. For example, China and Germany share a significant fraction of the total employment in this sector [132]. Especially, in the case of SWH products, the jobs mainly relate to the erection and installation of the system in houses. Jobs regarding renewable energy technologies exceeded 3.5 million in 2010. In general, developed economies contribute significantly in carrying out the technical improvement of the system while the developing countries also play a great role in training the skilled labor in taking care of the maintenance aspects.

5. Conclusions

This review paper primarily discussed the design features and related technical advancements of the SWH systems in terms of energy efficiency and cost effectiveness. One of the widely acknowledged benefits of the SWH systems is in the potential of energy savings. Therefore, the economic evaluation and the life cycle analysis are a necessary assessment to determine the feasibility of such systems. All of the economic evaluation factors that affect the SWH systems are also discussed in this review to find the specific energy efficient approaches depending on the size and particular energy demands. Using all of the discussed factors of this review, the actual penetration of the SWH systems in any demographic area can be assessed. This accurate economic potential assessment is necessary to increase the number of SWH consumers. Although few countries/places are more concerned in promoting SWH systems by overcoming all of the technical and economical barriers, it is not been equally promoted in the rest of the world because of several economical and technical issues. In this study it was observed that the installation of SWH systems are more feasible on a large area compared to small unit wise installation per households in terms of energy conservation and per unit energy cost over initial costs. In many large scale applications, such as commercial building sectors, both economical and technological feasibility assessment can contribute in the reduction of energy cost. In the case of packaged SWH units, currently many small enterprises are in the manufacturing stages worldwide. However, the cost and quality of the products are still not in the satisfactory level. More government rebates and benefits could help the small scale manufacturers to flourish more

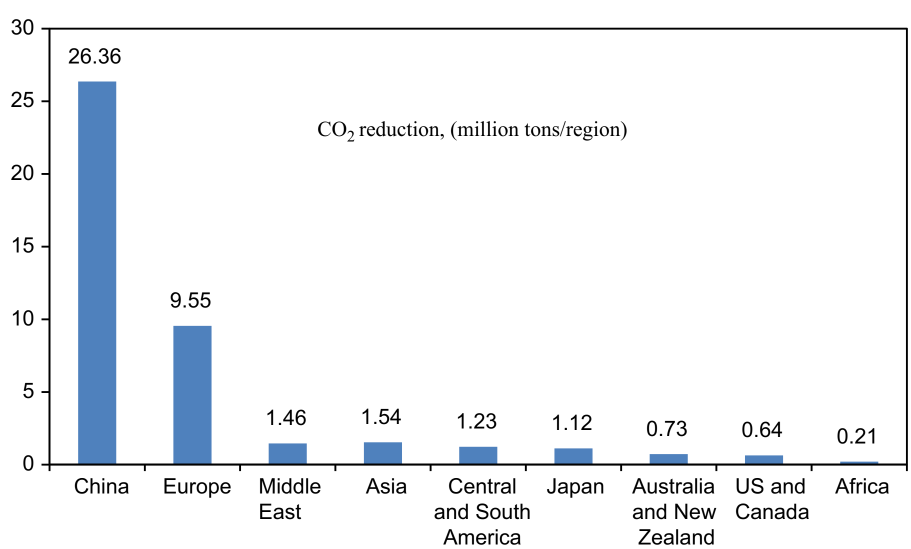

Fig. 23. Contribution to CO_2 reduction by flat-plate and evacuated tube collectors in operation by economic region in 2009 [139].

Table 7
Jobs in solar energy industries in the year 2010 [132].

Industry	Estimated jobs worldwide	No. job opportunities
Solar hot water	~300,000	China 250,000/Spain 7,000
Solar PV	~350,000	China 120,000/Germany 120,000/Japan 26,000/U.S. 17,000/Spain 14,000
Solar thermal power	~15,000	Spain 1,000/U.S. 1,000
Total existing renewable energy industries	> 3500,000	–

by maintaining quality assurance. Moreover, to ensure the quality of the SWH systems from large to small-scale, stricter quality control rules should be imposed, so that it can compete with the conventional water heating systems. The entry status of the SWH products in the market with respect to the product quality and supply is also a major requirement for the promotion of such SWH technologies. Environmental preferences and reliability are two competitive benefits of SWH systems in the international market. Finally, it can be said that the use of SWH systems can have a great impact on the economical, environmental, and energy conservation perspectives.

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References

[1] Langniss O, Ince D. Solar water heating: a viable industry in developing countries. Refocus 2004;5(3):18–21 May-June.
[2] Renewable Energy 2010: Key Facts and Figures for Decision Makers. Global status report. 〈http://www.ren21.net/gsr〉.
[3] 〈http://www.chinasolarwaterheaters.org/ks-german-solar-water-heater/〉.
[4] The Renewable Energy & Energy Efficiency Partnership (REEEP) 〈http://www.reeep.org/index.php?assetType=project&assetId=134〉.
[5] Renewable Energy Technologies, World Energy Assessment (WEA) Report 2001. 〈www.undp.org/seed/eap/activities/wea/drafts-frame.html〉.
[6] The Encyclopedia of Earth. 〈http://www.eoearth.org/article/De_Saussure,_Horace_B%C3%A9n%C3%A9dict〉.
[7] Butti K, Perlin J. A golden thread. London, UK: Marion Boyars Publishers Ltd; 1981.
[8] BD Chiaro, Solar water heating, how California can reduce its dependency on natural gas; Environment California Research and Policy Center, April 2007. 〈http://www.environmentcalifornia.org/uploads/at/56/at563bKwmfrtJI6fKl9U_w/Solar-Water-Heating.pdf〉.
[9] Butti K, Perlin J. Early solar water heaters, A Golden Thread. New York: Van Nostrand Reinhold Company; 1979 p. 117-127.
[10] Kalogirou SA. Solar energy engineering: processes and systems. London: Elsevier; 2009.
[11] The Equitable Building Heat Pump System. A National Historic Mechanical Engineering Landmark. Dedicated May 8, 1980 in Portland, Oregon. 〈http://www.bookrags.com/research/heat-pump-woi/〉 (access date: January 25, 2008).
[12] The unitary heat pump industry—25 years of progress. 〈http://adsabs.harvard.edu/abs/1977ASHRA.19.15P〉 (access date: September 19 2007).
[13] Zhang X, Plattern A, Shen L. Green property development practice in China: costs and barriers. Building and Environment 2011;46(11):2153–60.
[14] Kalogirou SA. Solar thermal collectors and applications. Progress in Engineering and Combustion Science 2004;30(3):231–95.
[15] Kalogirou S. Solar water heating in Cyprus: current status of technology and problems. Renewable Energy 1997;10(1):107–12.
[16] Close DJ. The performance of solar water heaters with natural circulation. Solar Energy 1962;6(1):33–40.
[17] DeSa VG. Experiments with solar energy utilization at Dacca. Solar Energy 1964;8(3):83–90 July-September.
[18] Gupta CL, Garg HP. System design in solar water heaters with natural circulation. Solar Energy 1968;12(12):163–70.
[19] Ong KS. A finite-difference method to evaluate the thermal performance of a solar water heater. Solar Energy 1974;16(3-4):137–47.
[20] Ong KS. An improved computer program for the thermal performance of a solar water heater. Solar Energy 1976;18(3):183–91.
[21] Sodha MS, Tiwari GN. Analysis of natural circulation solar water heating systems. Energy Conversion and Management 1981;21(4):283–8.
[22] Kudish AI, Santamaura P, Beaufort P. Direct measurement and analysis of thermosyphon flow. Solar Energy 1985;35(2):167–73.
[23] Morrison GL, Braun JE. System modeling and operation characteristics of thermosyphon solar water heaters. Solar Energy 1985;34(4-5):389–405.
[24] Uhlemann R, Bansal NK. Side-by-side comparison of a pressurized and a nonpressurized solar water heating thermosyphon system. Solar Energy 1985;34(4-5):317–28.
[25] Hobson PA, Norton B. A design nomogram for direct thermosyphon solar energy water heaters. Solar Energy 1989;43(2):89–95.
[26] Shariah A, Shalabi B. Optimal design for thermosyphon solar water heater. Renewable Energy 1997;11(3):351–61.
[27] Soin RS, Raghurman S, Murali V. Two-phase water heater model and long term performance. Solar Energy 1987;38(2):105–12.
[28] Soin RS, Rao KS, Rao DP, Rao KS. Performance of flat plate solar collector with fluid undergoing phase change. Solar Energy 1979;23(1):69–73.
[29] R Farrington,.M Deangelis,.L Morrison and D Dougherty, Performance evaluation of a refrigerant-charged thermosyphon solar DHW system. In Proc. AS/ISES annual meeting, Philadelphia, published by the ISES, American Section 1981; 4: 676–680.
[30] Bottum EW. Refrigerant charged phase change solar water heater and space heating systems. ASHRAE Transactions 1981;87(2):397–404.
[31] Fanny AH, Terlizzi CP. Testing of refrigerant-charged solar domestic hot water systems. Solar Energy 1985;35(4):353–66.
[32] Radhwan AM, Zaki GM, Jamil A. Refrigerant-charged integrated solar water heater. International Journal of Energy Research 1990;14(4):421–32.
[33] Akyurt M. AWSWAH—the heat pipe solar water heater. Journal of Engineering and Applied Science 1986;3:23–38.
[34] Kamal W. Performance evaluation of a refrigerant-charged solar collector. In Energex, 84. Regina, Saskatchewan: Pergamon Press; 1984 193-197.
[35] Radhwan AM, Zaki GM. Analysis of refrigerant-charged solar collectors with phase change. Hest Recovery Systems and CHP 1993;13(5):429–39.
[36] Pluta Z, Pomierny W. The theoretical and experimental investigation of the phase-change solar thermosyphon. Renewable Energy 1995;6(3):317–21.
[37] Payakaruk T, Terdtoon P, Ritthidech S. Correlations to predict heat transfer characteristics of an inclined closed two-phase thermosyphon at normal operating conitions. Applied Thermal Engineering 2000;20(9):781–90.
[38] Esen M, Esen H. Experimental investigation of a two-phase closed thermosyphon solar water heater. Solar Energy 2005;79(5):459–68.
[39] Chun W, Kang YH, Kwak HY, Lee YS. An experimental study of the utilization of heat pipes for solar water heaters. Applied Thermal Engineering 1999;19(8):807–17.
[40] Chien CC, Kung CK, Chang CC, Lee WS, Jwo CS, Chen SL. Theoretical and experimental investigations of a two-phase thermosyphon solar water heater. Energy 2011;36(1):415–23.
[41] Chen BR, Chang YW, Lee WS, Chen SL. Long-term thermal performance of a two-phase thermosyphon solar water heater. Solar Energy 2009;83(7): 1048–55.
[42] M Arab,.M Soltanieh, and MB Shafii, Experimental investigation of extra-long pulsating heat pipe application in solar water heaters. Experimental thermal and fluid science 2012; Available online 31 March: In Press, Accepted Manuscript.
[43] Directive 2006/40/EC of the European Parliament and of the Council of 17 May 2006 relating to emissions from air-conditioning systems in motor vehicles and amending Council Directive 70/156/EEC. Journal of the European Union 161, June 2006; 12–18.
[44] Yamaguchi H, Sawada N, Suzuki H, Ueda H, Zhang XR. Preliminary study on a solar water heater using supercritical carbon dioxide as working fluid. Journal of Solar Energy Engineering 2010;132(1):1–6.
[45] Ng KC, Yap C, Khor TH. Outdoor testing of evacuated-tube heat-pipe solar collectors. Proceedings of the Institution of Mechanical Engineers 2000;214: 23–30 (part E).
[46] Redpath DAG, Eames PC, Lo SNG, Griffiths PW. Experimental investigation of natural convection heat exchange within a physical model of the manifold chamber of a thermosyphon heat-pipe evacuated tube solar water heater. Solar Energy 2009;83(7):988–97.
[47] Jaisankar S, Ananth J, Thulasi S, Jayasuthakar ST, Sheeba KN. A comprehensive review on solar water heaters. Renewable and Sustainable Energy Reviews 2011;15(6):3045–50.
[48] Ho CD, Chen TC. Collector efficiency improvement of recyclic double-pass sheet-and tube solar water heaters with internal fin attached. Renewable Energy 2008;33(4):655–64.
[49] Budihardjo I, Morrison GL. Performance of water-in-glass evacuated tube solar water heaters. Solar Energy 2009;83(1):49–56.
[50] Tang R, Yang Y, Gao W. Comparative studies on thermal performance of water-in-glass evacuated tube solar water heaters with different collector tilt-angles. Solar Energy 2011;85(7):1381–9.
[51] Koffi PME, Andoh HY, Gbaha P, Toure S, Ado G. Theoretical and experimental study of solar water heater with internal exchanger using thermosiphon system. Energy Conversion and Management 2008;49(8):2279–90.
[52] Huang J, Pu S, Gao W, Que Y. Experimental investigation on thermal performance of thermosyphon flat-plate solar water heater with a mantle heat exchanger. Energy 2010;35(9):3563–8.
[53] Smyth M, Eames PC, Norton B. Integrated collector storage solar water heaters. Renewable and Sustainable Energy Reviews 2006;10(6):503–38.
[54] Chinnappa JCV, Gnanalingam K. Performance at Colombo, Ceylon, of a pressurized solar water heater of the combined collector and storage type. Solar Energy 1973;15(3):195–204.
[55] Mohamad AA. Integrated solar collector-storage tank system with thermal diode. Solar Energy 1997;61(3):211–8.
[56] Schmidt C, Goetzberger A. Single-tube integrated collector storage systems with transparent insulation and involute reflector. Solar Energy 1990;45(2):93–100.
[57] Sodha MS, Shukla SN, Tiwari GN. Thermal performance of n built in storage water heaters (or shallow solar ponds) in series. Solar Energy 1984;32(2):291–7.
[58] D Panico and G Clark, A general design method for integral passive solar water heaters. In Proceedings of the 9th national passive solar conference, Columbus, Ohio, USA. 1984; 81–86.
[59] Smyth M, Eames PC, Norton B. A comparative performance rating for an integrated solar collector/storage vessel with inner sleeves to increase heat retention. Solar Energy 1999;66(4):291–303.

[60] Kumer A, Tiwari GN. Transient analysis of collection-cum-storage water integrated with heat exchanger. Energy Conversion and Management 1988;28(3):201–6.
[61] Garg HP, Rani U. Theoretical and experimental studies on collector/storage type solar water heater. Solar Energy 1982;29(6):467–78.
[62] Prakash J, Garg HP, Datta G. Effect of baffle plate on the performance of built-in storage type solar water heater. Energy 1983;8(5):381–7.
[63] Kaptan IN, Kilic A. A theoretical and experimental investigation of a novel built-in-storage solar water heater. Solar Energy 1996;57(5):393–400.
[64] Chauhan RS, Kadambi V. Performance of a collector-cum-storage type of solar water heater. Solar Energy 1976;18(4):327–35.
[65] Sokolov M, Vaxman M. Analysis of an integral compact solar water heater. Solar Energy 1983;30(3):237–46.
[66] Ecevit A, Al-Shariah M, Apaydin ED. Triangular built-in-storage solar water heater. Solar Energy 1989;42(3):253–65.
[67] Shitzer A, Kalmoviz D, Zvirin Y, Grosman G. Experiments with a flat plate solar water heating system in thermosyphonic flow. Solar Energy 1979;22(1): 27–35.
[68] Shukla A, Buddhi D, Sawhney RL. Solar water heaters with phase change material thermal energy storage medium: a review. Renewable and Sustainable Energy Reviews 2009;13(8):2119–25.
[69] Prakash J, Garg HP, Datta G. A solar water heater with a built-in latent heat storage. Energy Conversion Management 1985;25(1):51–6.
[70] A Shukla, Heat transfer studies on phase change materials and their utilization in solar water heaters. Thesis Report, PhD Energy & Environment, Indore, India: School of Energy and Environmental Studies, Devi Ahilya University 2006.
[71] Galenen E, Van den Brink GJ. Energy storage in phase change materials for solar applications. International Journal of Ambient Energy 1986;7(1): 31–46.
[72] B Kumer, Design, development and performance evaluation of a latent heat storage unit for evening and morning hot water using a box type solar collector, M. Tech. (Energy Management), Indore, India: School of Energy and Environmental Stuies, Devi Ahilya University 2001.
[73] Reddy KS. Thermal modeling of PCM-based solar integrated collector storage water heating system. Journal of Solar Energy Engineering 2007;129(4): 458–64 November.
[74] Lane GA. Phase change thermal storage material. In: Guyer C, editor. Handbook of thermal design. Mc. Graw Hill Book Company; 1989.
[75] Hasan A. Phase change material energy storage system employing palmitic acid. Solar Energy 1994;52(2):143–54.
[76] Hasan A. Thermal energy storage system with stearic acid as phase change material. Energy Conversion Management 1994;35(10):843–56.
[77] Hasan A, Sayigh AA. Some fatty acids as phase change thermal energy storage materials. Renewable Energy 1994;4(1):69–76.
[78] Canbazoglu S, Sahinaslan A, Ekmekyapar A, Aksoy YG, Akarsu F. Enhancement of solar thermal energy storage performance using sodium thiosulfate pentahydrate of a conventional solar water-heating system. Energy Buildings 2005;37(3):235–42.
[79] Goetzberger A, Rommel M. Prospects for integrated storage collector systems in central Europe. Solar Energy 1987;39(3):211–9.
[80] Schmidt C, Goetzberger A, Schmid J. Test results and evaluation of integrated collector storage systems with transparent insulation. Solar Energy 1988;41(5):487–94.
[81] Garg HP, Hrishikesan DS, Jha R. System performance of built-in-storage type solar water heater with transparent insulation. Solar & Wind technology 1988;5(5):533–8.
[82] Prakash J, Garg HP, Hrishikesan DS, Jha R. Performance studies of an integrated solar collector-cum-storage water heating system with transparent insulation cover. Solar & Wind technology 1989;6(2):171–6.
[83] Mason AA, Davidson JH. Measured performance and modeling of an evacuated-tube, integral-collector-storage solar water heater. Journal of Solar Energy Engineering 1995;117(3):221–8.
[84] Reddy KS, Kaushika ND. Comparative study on transparent insulation materials cover systems for integrated-collector-storage solar water heaters. Solar Energy Materials and Solar Cells 1999;58(4):431–46.
[85] Tripanagnostopoulos Y, Yianoulis P. Integrated collector-storage systems with suppressed thermal losses. Solar Energy 1992;48(1):31–43.
[86] Tripanagnostopoulos Y, Souliotis M, Nousia Th. Solar ICS systems with two cylindrical storage tanks. Renewable Energy 1999;16(1-4):665–8.
[87] Tripanagnostopoulos Y, Souliotis M. ICS solar systems with horizontal (E–W) and vertical (N–S) cylindrical water storage tank. Renewable Energy 2004;29(1):73–96.
[88] Smyth M, Eames PC, Norton B. Heat retaining integrated collector/storage solar water heaters. Solar Energy 2003;75(10):27–34.
[89] Smyth M, Eames PC, Norton B. Techno-economic appraisal of an integrated collector/storage solar water heater. Renewable Energy 2004;29(9): 1503–14.
[90] Kalogirou S. Design, construction, performance evaluation and economic analysis of an integrated collector storage system. Renewable Energy 1997;12(2):179–92.
[91] Tripanagnostopoulos Y, Souliotis M, Nousia Th. CPC type integrated collector storage systems. Solar Energy 2002;72(4):327–50.
[92] Helal O, Chaouachi B, Gabsi S. Design and thermal performance of an ICS solar water heater based on three parabolic sections. Solar Energy 2011;85(0):2421–32.
[93] Smyth M, McGarrigle P, Eames PC, Norton B. Experimental comparison of alternative convection suppression arrangements for concentrating integral collector storage solar water heaters. Solar Energy 2005;78(2):223–33.
[94] Li Z, Chen C, Luo H, Zhang Y, Xue Y. All-glass vacuum tube collector heat transfer model used in forced-circulation solar water heating system. Solar Energy 2010;84(8):1413–21.
[95] A Walker,.F Mahjouri and R Stiteler, Evacuated-tube heat-pipe solar collectors applied to recirculation loop in a federal building: SSA Philadelphia. ASME 2004 International Solar Energy Conference (ISEC2004) Paper no. ISEC2004-65132; 217–222.
[96] Chong KK, Chay KG, Chin KH. Study of a solar water heater using stationary V-trough collector. Renewable Energy 2011;39(1):207–15.
[97] Chaturvedi SK, Chen DT, Kheireddine A. Thermal performance of a variable capacity direct expansion solar-assisted heat pump. Energy Conversion Management 1998;39(3-4):181–91.
[98] Hawlader MNA, Chou SK, Jahangeer KA, Rahman SMA, Lau KWE. Solar-assisted heat-pump dryer and water heater. Applied Energy 2003;74(1-2):185–93.
[99] Chyng JP, Lee CP, Huang BJ. Performance analysis of a solar-assisted heat pump water heater. Solar Energy 2003;74(1):33–44.
[100] Kuang YH, Sumathy K, Wang RZ. Study on a direct-expansion solar-assisted heat pump water heating system. International Journal of Energy Research 2003;27(5):531–48.
[101] Li YW, Wang RZ, Wu JY, Xu YX. Experimental performance analysis on a direct-expansion solar-assisted heat pump water heater. Applied Thermal Engineering 2007;27(17-18):2858–68.
[102] Hepbasli A. Exergetic modeling and assessment of solar assisted domestic hot water tank integrated ground-source heat pump systems for residences. Energy and Building 2007;39(12):1211–7.
[103] Huang BJ, Lee JP, Chyng JP. Heat-pipe enhanced solar-assisted heat pump water heater. Solar Energy 2005;78(3):375–81.
[104] Guoying X, Xiaosong Z, Shiming D. A simulation study on the operating performance of a solar-air source heat pump water heater. Applied Thermal Engineering 2006;26(11-12):1257–65.
[105] Duffie JA, Beckman WA. Solar engineering of thermal processes. New York: John Wiley; 1980 pp. 487-488.
[106] Sakai I, Terakawa MT, Ohue J. Solar space heating and cooling with bi-heat source heat pump and hot water supply system. Solar Energy 1976;18(6): 525–32.
[107] Morrison GL, Anderson T, Behnia M. Seasonal performance rating of heat pump water heaters. Solar Energy 2004;76(1-3):147–52.
[108] Ito S, Miura N. Studies of a heat pump using water and air sources in parallel. Heat Transfer Asian Research 2000;29(6):473–90.
[109] Zhang J, Wang RZ, Wu JY. System optimization and experimental research on air source heat pump water heater. Applied Thermal Engineering 2007;27(5-6):1029–35.
[110] Ji J, Chow T, Pei G, Dong J, He W. Domestic air-conditioner and integrated water heater for subtropical climate. Applied Thermal Engineering 2003;23(5):581–92.
[111] Williams PM, Klein SA, Beckman WA, Mitchell JW. Modeling PV powered solar water heating systems using TRNSYS. American Solar Energy Society, SOLAR 1997;97:341–6.
[112] GL Morrison and BD Wood, Packaged solar water heating technology: twenty years of progress. Proceedings of ISES solar world congress on CD-ROM, Jerusalem, Israel; 1999.
[113] Xu G, Zhang X, Deng S. Experimental study on the operating characteristics of a novel low-concentrating solar photovoltaic/thermal integrated heat pump water heating system. Applied Thermal Engineering 2011;31(17-18): 3689–95.
[114] Voivontas D, Tsiligiridis G, Assimacopoulos D. Solar potential for water heating explored by GIS. Solar Energy 1998;62(6):419–27.
[115] JJ Mutch, Residential water heating: fuel conservation, economics and public policy. 1974 RAND Report, R 1498.
[116] Chandrasekar B, Kandpal TC. Techno-economic evaluation of domestic solar water heating systems in India. Renewable Energy 2004;29(3):319–32.
[117] Pillai IR, Banerjee R. Methodology for estimation of potential for solar water heating in a target area. Solar Energy 2007;81(2):162–72.
[118] P Denholm, The technical potential of solar water heating to reduce fossil fuel use and greenhouse gas emissions in the United States. Technical Report NREL/TP-640-41157 March 2007.
[119] Pan TC, Kao JJ, Wong CP. Effective solar radiation based benefit and cost analyses for solar water heater development in Taiwan. Renewable and Sustainable Energy Reviews 2012;16(4):1874–82.
[120] Beckman WA, Klein SA, Duffie JA. Solar heating design by the f-chart method. New York: Wiley Interscience; 1977.
[121] Break-even cost for residential solar water heating in the United States, National Renewable Energy Laboratory. 〈http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/ns/webinar_lowcost_swh_roadmap_20110728.pdf〉 (accessed July 28, 2011).
[122] Xiaowu W, Ben Hua. Exergy analysis of domestic-scale solar water heaters. Renewable and Sustainable Energy Reviews 2005;9(6):638–45.
[123] Kulkarni GN, Kedare SB, Bandyopadhyay S. Design of solar thermal systems utilizing pressurized hot water storage for industrial applications. Solar Energy 2008;82(8):686–99 August.
[124] Diakoulaki D, Zervos A, Sarafidis J, Mirasgedis S. Cost benefit analysis for solar water heating systems. Energy Conversion and Management 2001;42(14): 1727–39.

[125] ENERGY STAR® Residential Water Heaters: Draft Criteria Analysis. 〈http://www.energystar.gov/ia/partners/prod_development/new_specs/downloads/water_heaters/WaterHeaterDraftCriteriaAnalysis.pdf〉.
[126] ASHRAE 90003, Active Solar Heating Systems Design Manual, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329; ISBN 0-910110-54-9, 1988.
[127] Srinivas M. Domestic solar hot water systems: developments, evaluations and essentials for "viability" with a special reference to India. Renewable and Sustainable Energy Reviews 2011;15(8):3850–61.
[128] Misra RS. Techno-economic optimization of thermosyphonic solar hybrid water heating systems. Energy Conversion and Management 1994;35(3):205–17.
[129] Nagaraju J, Garud SS, Kumar KA, Rao MR. 1 MWth industrial solar hot water system and its performance. Solar Energy 1999;66(6):491–7.
[130] Muneer T, Maubleu S, Asif M. Prospects of solar water heating for textile industry in Pakistan. Renewable and Sustainable Energy Reviews 2006;10(1):1–23.
[131] Sok E, Zhuo Y, Wang S. Performance and economic evaluation of a hybrid photovoltaic/thermal solar system in Northern China. World Academy of Science, Engineering and Technology 2010;72:176–81.
[132] REN21 Renewables 2011 Global Status Report. 〈http://www.ren21.net〉.
[133] L Sherwood. U.S. solar market trends 2010. Interstate Renewable Energy Council (IREC), June 2011.
[134] Renewable Energy Annual 2008 U.S. Energy Information. Administration Office of Coal, Nuclear, Electric and Alternate Fuels, U.S. Department of Energy. (Release Date: August 2010) 〈http://www.eia.doe.gov〉.
[135] BD Wood and J He, The real value of solar domestic hot water systems, Proceedings cooperative clean air technology, air and waste management association, SP-83, March 29-April 1, 1992.
[136] California Energy Commission (1998), Energy Technology Division, 1516 9th Street, Sacramento, California, USA. 〈http://www.energy.ca.gov/〉.
[137] World Building Design Guide (a program of the National Institute of Building Sciences). "Solar Water Heating." Updated by U.S. Department of Energy. 2011. 〈http://www.wbdg.org/resources/swheating.php〉 (accessed August 03, 2011).
[138] CJ Colon,.DS Parker. Side-by-side testing of water heating systems: results from the 2009-2010 evaluation. (FSEC-CR-1856-10) Florida Solar Energy Center. Submitted to: U.S. Department of Energy. June 2010.
[139] W Weiss,.F Mauthner. Solar heat worldwide, markets and contribution to the energy supply 2009. Solar Heating and Cooling Program, International Energy Agency. May 2011.
[140] Fanney AH, Dougherty BP. A photovoltaic solar water heating system. ASME Journal of Solar Energy Engineering 1997;119:126–33.